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RADIATION THROUGH A FOGGY ATMOSPHERE

By ARTHUR SCHUSTER

1. In discussing the transmission of light through a mass of gas, it is usual to consider only the effects of emission and absorption, and to neglect all effects of scattering. But when the absorbing mass holds fine particles of matter in suspension, the scattered light materially affects the character of the transmitted radiation. I propose to discuss the conditions under which "bright line" spectra or "dark line" spectra may be obtained from a radiating mass of gas, taking account of scattering. I call an atmosphere "foggy" when scattering takes place to an appreciable extent. The applications of the results of this investigation are, however, much wider than the title chosen would seem to imply, for there is some scattering even from the molecules of a homogeneous substance, and to that extent all bodies fall within the definition and may be called "foggy."

According to the investigations of Lord Rayleigh, the greater part of the light we receive from the sky is due to light scattered by the molecules of the air. This involves a diminution in the intensity of the direct rays amounting in our atmosphere to roughly 5 per cent. The effective thickness of stellar atmospheres may be great compared with that of the shell of air which surrounds our globe, and hence the effects of scattering may be of primary importance in interpreting the nature of stellar atmospheres.

2. The following notation will be used:

E=the total energy of radiation within a certain small range of wave-lengths sent out by unit surface of a completely black surface. E is a function of the temperature and wave-length.

S=the total energy of radiation incident within the same limit of wave-lengths on unit surface of a plane layer of the foggy gas.

R=the energy which leaves the plane layer per unit surface.

R_o=the particular value of R for the case that there is no absorption.

R_c=the particular value of R for rays which are completely absorbed by an infinitely thin layer.

κ=the coefficient of absorption.

s=the coefficient of scattering.

The object of the investigation is to determine R in terms of S and E, if E refers to the temperature of the foggy gas. It will save needless repetition if it is understood once for all that our statements always refer to unit surface of the radiating or absorbing layer.

κ is a function of the wave-length which also depends on the density of the medium. If the medium is uniform, all molecules absorbing alike, κ would be proportional to the density. But in a mixture of different gases, κ must be considered proportional only to the quantity (measured per unit volume) of the particular substance which absorbs the wave-length in question. Similarly s depends on the number of the scattering particles, the scattering and absorbing particles not necessarily being of the same nature. If the scattering is of the nature of that which causes the blue color of the sky, the value of s varies inversely as the fourth power of λ, but in case of an ordinary cloud or mist, the dependence on wave-length is much less marked.

If S be the total intensity of radiation incident on a layer of small thickness dx, the radiation absorbed by the layer is $\kappa S dx$. The light emitted by the same layer in each direction is thus $\kappa E dx$. This follows from the law connecting absorption and radiation.

The light scattered by the layer is $sSdx$, of which one-half is sent forward and one-half returned backward.

The following variables will be introduced for convenience of expression:

$$\beta=\kappa/s \ ,$$
$$\alpha=\sqrt{\kappa/(\kappa+s)}=\sqrt{\beta/(1+\beta)} \ ,$$
$$\therefore \beta=\alpha^2/(1-\alpha^2) \ .$$

β varies from zero to infinity, but a must lie between zero and unity.

$$\gamma=(1+a)/(1-a) \; ,$$
$$\therefore \gamma=1+2\beta+\sqrt{\beta+\beta^2} \; .$$

3. Let (Fig. 1) S_1S_2 be a surface sending out the radiation S, and let this radiation after passing through part of the foggy atmosphere be reduced to a value A and fall on a thin layer of thickness dx. The effect of the layer is to absorb energy amounting to $\kappa A dx$, and additionally to reduce the incident light by a quantity $sAdx$, which is not absorbed, but sent in equal amounts backward and forward as scattered light. If the stream of radiant energy in the opposite direction is B, we have similarly a diminution of energy equal to $(\kappa+s)\,B$, of which, however, $\frac{1}{2}sB$ is sent both forward and backward as scattered light. The layer also radiates energy in both directions equal to $\kappa E dx$. Collecting these effects, we obtain the equations:

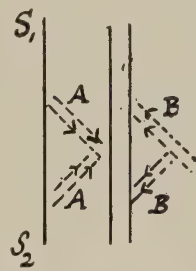

FIG. 1.

$$\frac{dA}{dx}=\kappa(E-A)+\tfrac{1}{2}s(B-A) \tag{1}$$

$$\frac{dB}{dx}=\kappa(B-E)+\tfrac{1}{2}s(B-A) \; . \tag{2}$$

Combining (1) and (2) we find:

$$\frac{d(A+B)}{dx}=(\kappa+s)(B-A) \tag{3}$$

$$\frac{d(A-B)}{dx}=2\kappa E-\kappa(A+B) \; . \tag{4}$$

Differentiating (3) and with the help of (4)

$$\frac{d^2(A+B)}{dx^2}=\kappa(\kappa+s)(A+B-2E) \; . \tag{5}$$

If E is constant or varies uniformly with x, the last equation may be integrated, and we derive:

$$(A+B-2E)=Ke^{(\kappa+s)ax}+K_1e^{-(\kappa+s)ax} \tag{6}$$

where K and K_1 are two constants and a has the value assigned to it in § 2.

If the temperature of the medium is constant, so that E has the same value throughout the scattering medium, differentiation gives

$$\frac{d(A+B)}{dx}=a(\kappa+s)\left(K_1e^{(\kappa+s)ax}-K_1e^{-(\kappa+s)ax}\right) \qquad (7)$$

and hence by introducing (3)

$$B-A=a\left(Ke^{(\kappa+s)ax}-K_1e^{-(\kappa+s)ax}\right) . \qquad (8)$$

Equations (6) and (8) now allow us to obtain A and B separately, and we thus find:

$$\left.\begin{aligned}2A&=2E+(1-a)Ke^{(\kappa+s)ax}+(1+a)K_1e^{-(\kappa+s)ax}\\ 2B&=2E+(1+a)Ke^{(\kappa+s)ax}+(1-a)K_1e^{-(\kappa+s)ax}\end{aligned}\right\} . \qquad (9)$$

We consider x to be measured from the front surface of the foggy medium in the direction in which the radiation A proceeds. If no radiation enters the medium from the opposite direction, and if the radiation incident in the first absorbing layer be S, we have the conditions:

$$\left.\begin{aligned}&\text{for } x=0; \qquad B=0\\ &\text{for } x=-t; \qquad A=S\end{aligned}\right\} \qquad (10)$$

the thickness of the medium being denoted by t.

We require to determine the emergent radiation which is equal to the value which A acquires when $x=0$. Denoting this by R, we have from the first of equations (9)

$$2R=2E+(1-a)K+(1+a)K_1 . \qquad (11)$$

Introducing (10) into (9) allows us to determine K and K_1. We obtain in the first place the equations

$$0=2E+(1+a)K+(1-a)K_1$$

$$2S=2E+(1-a)Ke^{-a(\kappa+s)t}+(1+a)K_1e^{a(\kappa+s)t} ,$$

and these give

$$K=\frac{2\left[(1-a)-(1+a)e^{a(\kappa+s)t}\right]E-2(1-a)S}{(1+a)^2e^{a(\kappa+s)t}-(1-a)^2e^{-a(\kappa+s)t}} ,$$

$$K_1=\frac{2\left[(1-a)e^{-a(\kappa+s)t}-(1+a)\right]E+2(1+a)S}{(1+a)^2e^{a(\kappa+s)t}-(1-a)^2e^{-a(\kappa+s)t}} .$$

Finally by substitution into (11)

$$R=2a\frac{\left[(1+a)e^{a(\kappa+s)t}+(1-a)e^{-a(\kappa+s)t}\right]E+2(S-E)}{(1+a)^2e^{a(\kappa+s)t}-(1-a)^2e^{-a(\kappa+s)t}} . \qquad (12)$$

Equation (12) contains the solution of our problem.

4. The equations of the last paragraph have been deduced under the assumption that the radiation throughout the absorbing mass is uniformly distributed in such a way that it does not depend on the angle between any direction considered and the normal drawn toward the same side. This supposition is obviously incorrect, for it appears that, even if it were to hold at any surface, e. g., the first surface of the layer dx (Fig. 1), absorption in that layer would destroy the uniformity owing to the greater absorption which the oblique rays suffer. To some extent the effect of scattering would act in the sense of partly restoring the equality of distribution; nevertheless serious errors might be introduced, if we attempted to obtain accurate values of κ and s by means of the application of equation (12). The complete investigation leads to equations of such complexity that a discussion becomes impossible, and I shall only use the solution obtained under the simplified conditions to deduce certain consequences which cannot be affected by the assumption made. The error committed might be allowed for by taking s and κ to be functions of the distance. When considered in this light, it is seen how useless the more complete calculation would be, because in the more important cases to which we have to apply our results, the coefficients of scattering and absorption vary in an unknown manner, and the error committed by the simplification of this problem becomes merged in other unavo d-able uncertainties.

5. Before discussing the general results contained in equation (12) we may treat separately of some simple special cases. When the coefficient of absorption, and consequently α, is zero, we require to express the exponentials of (12) in a series, the first two terms being retained. But it is easier in this case to proceed directly. Equations (3) and (4) in this case become

$$\frac{d(A+B)}{dx}=s(B-A) \ ,$$

$$\frac{d(A-B)}{dx}=0 \ .$$

The second equation shows that $A-B$ is a constant which must be equal to R_0, the value of A at the front surface. The first equation may now be integrated, and gives

$$A+B=a-sR_0x \ .$$

As for $x=0$, $B=0$, and $A=R_0$, it follows that $a=R_0$; or replacing B by $A-R$,

$$2(A-R_0)=-sR_0x \ .$$

When $x=-t$, the value of A is equal to S, the incident radiation, hence

$$2(S-R_0)=sA_0t \ ;$$

or finally:

$$R_0=\frac{2}{2+st}S \ . \tag{13}$$

The equation shows that the emergent radiation diminishes with increasing thickness, but not so quickly as it would do if scattering acted in the same manner as absorption. If, for instance, we give to st the numerical value of ninety-eight, so that the emergent light is 2 per cent. of the incident light, doubling the layer would still give us 1 per cent. for the transmitted light, and with greater thicknesses the light would, roughly speaking, be inversely proportional to the thickness. But in the case of absorption, the double layer would only transmit 2 per cent. of 2 per cent., and the transmitted light would diminish in a geometric ratio, while the thickness increases in an arithmetic ratio.

6. When either st or κt is so large that practically no part of the original light is transmitted, we may neglect in (12) all terms except those containing an exponential with a positive argument, and this gives at once

$$R_c=\frac{2a}{1+a}E \tag{14}$$

When κ is large compared with s, a approaches unity and ultimately $R_c=E$. The radiation in that case becomes equal to that of a completely black surface, which agrees with the well-known law that absorption irrespective of scattering tends to make the radiation of all bodies equal to that of a black body when the thickness is increased.

But, as has been mentioned, scattering always exists, and has to be taken into account. It appears from the definition of a that it is always a fraction, and hence the factor of E in (14) is always smaller than one. It follows that the emergent radiation increases with the value of κ, and hence a luminous gas always gives a spec-

trum of bright lines, and does not approach with increasing thickness to the radiation from a black body, as it would do in the absence of scattering.

7. It is not possible to discuss equation (12) in its general form. In order to draw the appropriate conclusions in certain typical cases, we introduce other variables.

Put

$$e^{st}=r\ ; \qquad \beta=\kappa/s\ ,$$

and introduce a quantity γ defined by

$$\gamma=\frac{1+a}{1-a}\ .$$

We have then

$$a(\kappa+s)t=st(1+\beta)a\ ;$$

and also

$$a=\sqrt{\beta/(1+\beta)}\ .$$

Hence

$$\gamma=1+2\beta+2\sqrt{\beta+\beta^2} \tag{15}$$

$$\frac{2a}{1-a}=\gamma-1\ ,$$

$$\frac{2a(1+a)}{(1-a)^2}=\frac{1+a}{1-a}\cdot\frac{2a}{1-a}=\gamma(\gamma-1)\ ,$$

$$\frac{4a}{(1-a)^2}=\gamma^2-1\ .$$

Equation (12) now becomes

$$R=(\gamma-1)\frac{(\gamma r^{\sqrt{\beta+\beta^2}}+r^{-\sqrt{\beta+\beta^2}})E-(\gamma+1)(E-S)}{\gamma^2 r^{\sqrt{\beta+\beta^2}}-r^{-\sqrt{\beta+\beta^2}}}. \tag{16}$$

As (15) gives γ in terms of β, all factors of E and S are now expressed in terms of β and st. I have carried out the calculations for the three cases that st is equal to $\frac{1}{2}$, 1, and 2, respectively, and for a number of different values of β. If we calculate the coefficient in (16) and write it (16) in the form

$$R=aE+bS\ ,$$

Table I gives the coefficients of a and b.

TABLE I

		0.1	0.8	1	1.2	2	10
$st = 0.5$	a	0.0486	0.3258	0.3872	0.4428	0.6165	0.9762
	b	0.7604	0.5333	0.4820	0.4355	0.2911	0
$st = 1$	a	0.0944	0.5276	0.6019	0.6626	0.8142	0.9762
	b	0.6000	0.2902	0.2364	0.1926	0.0855	0
$st = 2$	a	0.1760	0.7147	0.7716	0.8111	0.8895	0.9762
	b	0.3971	0.0872	0.0574	0.0379	0.0074	0

The relative intensities of the dark and bright lines as they would appear in the special cases considered will be most easily under-

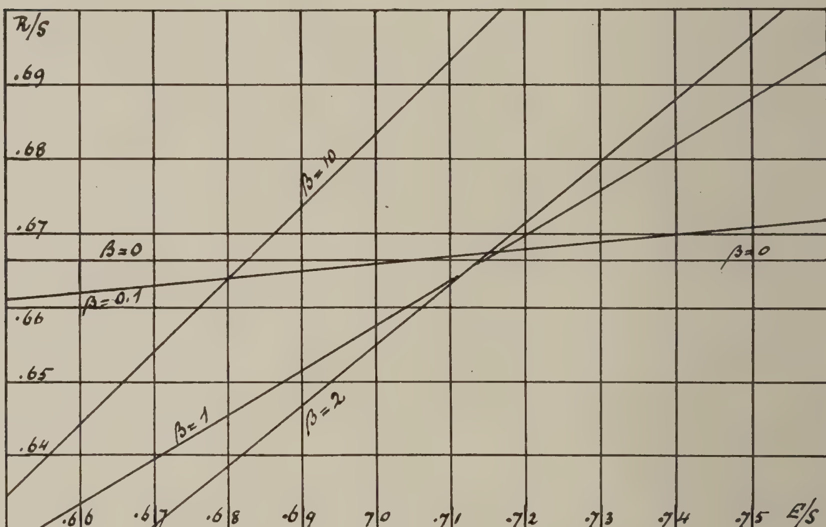

FIG. 2. $st = 1$.

stood if straight lines are drawn (Fig. 2) with E/S as abscissæ and R/S as ordinates. That figure refers to the case $st = 1$. The horizontal line marked $\beta = 0$ gives R_0/S, which defines the intensity of the transmitted light when there is no absorption. The value of R_0/S is obtained from (13), which shows that for $st = 1$, only two-thirds of the incident light traverses the scattering medium. If this medium is capable of sending out any vibration defined as regards radiative power by the fraction $\beta = \kappa/s$, the corresponding intensity may be

obtained from the curve by taking on the horizontal axis the magnitude E/S, which is the intensity of the black radiation at the temperature of the absorbing and scattering medium in terms of that of the incident light. The corresponding ordinate gives the transmitted light in terms of the same unit. If the point of the straight line corresponding to any particular value of β lies above the horizontal line marked $\beta = 0$, the appearance will be that of a bright line; if it lies below, a dark line would be observed. Starting with a comparatively low temperature of the foggy medium and gradually increasing it (i. e., gradually increasing the ordinates), it is seen that at first all homogeneous vibrations appear as dark lines, and if the temperature is sufficiently low (not shown in figure) the highest values of β give the greatest deficiency of light. This is in accordance with what takes place in the absence of scattering.

When the temperature is gradually raised, the most intense line represented in the figure ($\beta = 10$) ceases to be the darkest line, and ultimately when E/S is about 0.682, this line becomes brighter than the background. The next line to change from darkness to brightness is the line of lowest intensity $\beta = 0.1$, and when E/S is more than 0.715, all the lines are bright. The change from dark to bright lines takes place within a comparatively small range of temperature; nevertheless the possibility of the simultaneous appearance of dark and bright lines according to the intensity of absorption is shown by the figure. If, instead of a homogeneous line, we contemplate the case of narrow bands such as frequently occur, we must consider β to have a maximum value at the center of the band (e. g., $\beta = 10$) and to fall off on either side more or less rapidly to zero. At very low temperatures of the medium, the center of the band in this case would be darkest and at high temperatures brightest. But intermediate temperatures would give the appearance of a bright central line on a dark absorption band. Thus at a temperature of 0.69, the brightness of the center ($\beta = 10$) in terms of the intensity of the transmitted light is 0.674, which means that it is 1.2 per cent. brighter than the background, while towards both sides, where β has fallen to 2, the intensity is 0.637 or 4.5 per cent. darker than the background. The appearance is therefore that of an absorption band with a reversed line in the center.

Fig. 3 gives the diagram of radiation for $st=0.5$. It is drawn to a somewhat larger scale than Fig. 2.

Fig. 4 represents the connection between transmitted light and coefficient of absorption when $st=2$. In this case the unabsorbed radiation is scattered to the extent that only half the incident light is transmitted. The possibility of the simultaneous appearance of dark and bright lines, which carries with it the possibility of an absorption band with a reversed line at the center, is increased in

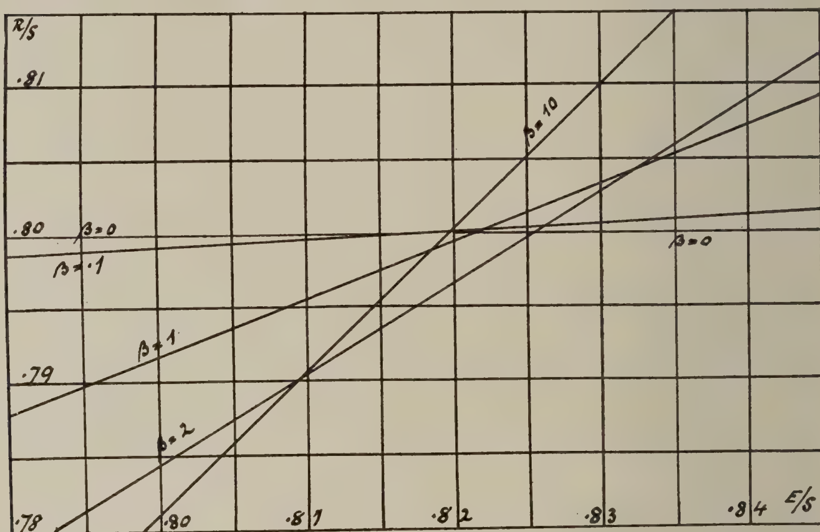

FIG. 3. $st=0.5$.

this case. Thus when E/S is 0.54, a line defined by $\beta=10$, shows an increase in brightness over the background $[(R-R_0)/R_0]$ of 5.4 per cent. and a weaker line ($\beta=1$) gives a deficiency of light of 5.2 per cent.

Table II gives the values of E/S at which the transmitted radiation corresponding to different values of β is equal to that of the transmitted unabsorbed radiation ($\beta=0$). The numbers given define the temperatures of the absorbing medium at which the transition from the dark to the bright lines takes place.

Table III gives in terms of R_0 the intensities of the radiations when the temperature of the absorbing layer is the same as that of the background, the incident light S being in this case considered

to emanate from a black body. The table shows the importance of the effects of scattering on the production of bright line spectra; for, neglecting this scattering, all the numbers would be equal to unity, and we should only obtain the continuous spectrum of the background, the medium not affecting the radiation at all.

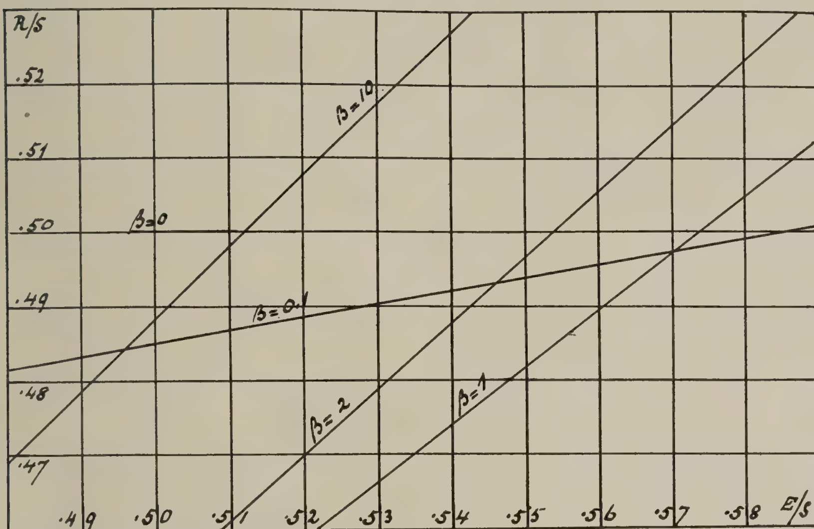

FIG. 4. $st=2$.

TABLE II

	$\beta=$	0.1	0.8	1	1.2	2	10
$st=0.5$...	$\frac{0.8-a}{b}$	0.8149	0.8185	0.8213	0.8231	0.8254	0.8196
$st=1$....	$\frac{0.6667-a}{b}$	0.7065	0.7137	0.7150	0.7155	0.7139	0.6831
$st=2$....	$\frac{0.5-a}{b}$	0.5845	0.5776	0.5736	0.5697	0.5539	0.5123

TABLE III

	$\beta=$	0.1	0.8	1	1.2	2	10
$st=0.5$...	$\frac{a+b}{0.8}$	1.011	1.074	1.086	1.098	1.134	1.220
$st=1$....	$\frac{3}{2}(a+b)$	1.042	1.227	1.257	1.283	1.350	1.464
$st=2$....	$2(a+b)$	1.146	1.604	1.658	1.698	1.794	1.952

8. In the problem as it is usually considered, absorption is introduced by having a cooler medium of uniform temperature in front of a hotter one, and the change of temperature is taken to be an abrupt one. But in considering the phenomena of radiation presented to us by celestial bodies, we must bear in mind that no such discontinuous variation in temperature is admissible. It seems therefore desirable to discuss, even if only in a very simple case, the radiation emitted by a gas of continuously varying temperature.

Equation (6) holds when the temperature variation of the medium is such that the radiation of a black body for the particular wave-length considered varies uniformly with x. We write now for the equation defining the temperature of the medium: $E=j-ux$, where j represents the radiation of a black body which is at the temperature of the external surface of the medium, and u being positive, the temperature increases toward the inside. By differentiation of (6) and the application of (3) we then obtain

$$(B-A)=-\frac{2u}{\kappa+s}+Kae^{(\kappa+s)ax}-K_1ae^{-(\kappa+s)ax}$$

Combining this with (6) we find

$$2A=2(j-ux)+\frac{2u}{\kappa+s}+K(1-a)e^{(\kappa+s)ax}+K_1(1+a)e^{-(\kappa+s)ax} \qquad (17)$$

At a certain distance, for which we may put $x=-t$, we may imagine a radiating black surface to be placed, having a temperature equal to that of the medium at that surface. The incident radiation A must therefore here coincide with the radiation E.
This gives

$$A=j+ut \ .$$

If t is very large, we find by applying (17) to this distant layer

$$0=\frac{2u}{\kappa+s}+K_1ae^{(\kappa+s)at} \ ,$$

which gives for K_1 negligible values when t is sufficiently large.
Putting $x=0$ in (17), we now obtain

$$2R=2j+\frac{2u}{\kappa+s}+K(1-a) \ .$$

If we apply (6) to the case of $x=0$ when $B=0$, $A=R$, $E=j$, we also find, neglecting K_1,

$$R=2j+K \ .$$

Hence, eliminating K,

$$(1+a)R=2af+\frac{2u}{(\kappa+s)} . \tag{18}$$

The character of the radiation is seen from this equation to depend on the relative values of the radiation-gradient and the coefficient of scattering. In order to exemplify the conditions which regulate the nature of the spectrum, draw a plane through the medium at a distance t behind the front surface. Choose t to be such that, owing to scattering and independently of absorption, only 0.8 of the light incident on the layer passes through it. This gives $st=1$. Let $(1+m)f$ be the radiation passing through the plane at a distance t from the front surface. The temperature of the scattering medium varies therefore in such a manner that the radiation of a black body increases in the ratio $(1+m) : 1$, when $t=1/S$. As the radiation generally is $f-ux$, we have, when $st=1$,

$$f+ut=(1+m)f ,$$

or

$$ut=mf .$$

If in the second term of (18) we multiply numerator and denominator by t and substitute $st=1$, $\kappa t=\kappa/s=\beta$, we find

$$R=2f\left(\frac{a}{1+a}+\frac{m}{(1+\beta)(1+a)}\right) ,$$

$$=2f\left[\frac{a}{1+a}+m(1-a)\right] \tag{19}$$

It remains to discuss this equation. For $\beta=0$,

$$R_0=2mf$$

and this may be taken to be the intensity of the continuous background of the spectrum. If the radiative power of any homogeneous radiation is very large, so that β is very large,

$$R_c=f .$$

The lines with large radiative power appear therefore bright or dark according as m is less or greater than one-half.

Differentiating (19) with respect to a,

$$\frac{dR}{da}=2f\left[\frac{1}{(1+a)^2}-m\right] ,$$

we see that as a increases from zero, the radiation increases or dimin-

ishes according as m is smaller or greater than one. A turning-point is reached when

$$m=\frac{1}{(1+a)^2},$$

or

$$a=\frac{1}{\sqrt{m}}-1 \tag{20}$$

As a is necessarily positive and smaller than one, this turning-point has a meaning applicable to our problem only when m is greater than one-quarter and smaller than unity. A maximum of radiation is reached in this case, and for values of the coefficient of absorption greater than those defined by (20) the radiation diminishes again. The radiation reaches the same value it has for $a=0$, when

$$R=R_0,$$

or

$$m=\frac{a}{1+a}+m(1-a),$$

or

$$m=\frac{1}{1+a}.$$

As a is a positive fraction, it follows that in order that $R=R_0$ for a second value of a, it is necessary that m should be greater than one-half.

When there is a maximum, its value is easily found to be

$$R=2f[m+(1-\sqrt{m})^2].$$

We may summarize our results thus:

Case I: $m<\frac{1}{4}$.—With increasing coefficient of absorption, the radiation increases. All homogeneous vibrations appear as bright lines. The brightness of the background ($\kappa=0$) is given by

$$R_0=2mf;$$

that of the brightest line

$$R_c=f.$$

Case II: $\frac{1}{4}<m<\frac{1}{2}$.—With increasing coefficient of absorption the radiation increases and reaches a maximum when

$$a=\frac{1}{\sqrt{m}}-1.$$

For greater values of a, the radiation diminishes. All lines are bright, but the lines with the greatest coefficient of absorption are not the brightest. Thus when $m=\frac{1}{2}$, the maximum radiation takes place when $a=0.414$ ($\beta=0.207$), and gives an intensity of $1.172\,f$, while for infinite values of κ the intensity is f.

Case III: $\frac{1}{2}<m<1$.—The intensity rises to a maximum as in Case II, then diminishes until, when $a=\frac{1-m}{m}$, the radiation has the

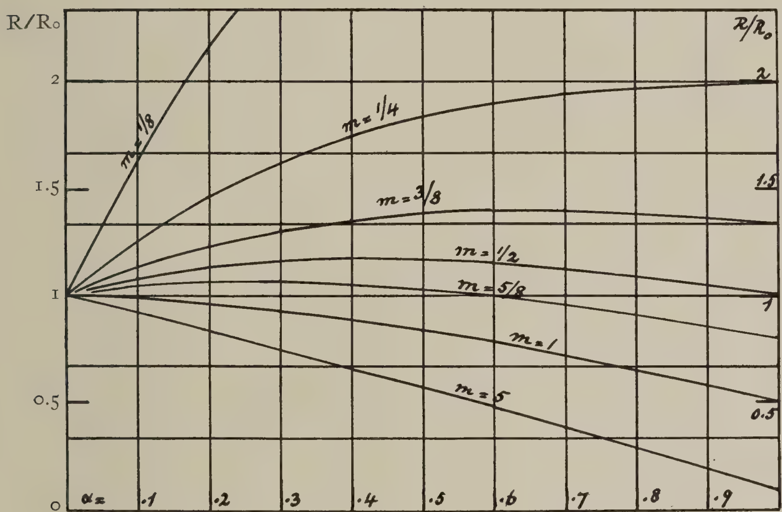

FIG. 5.

same value as when $a=0$. After this point it diminishes. Homogeneous radiations will in this case appear as bright lines when $a>\frac{1-m}{m}$ and as dark lines for greater values of a.

Case IV: $m>1$.—The intensity diminishes continuously with increasing coefficient of absorption. All homogeneous lines appear as dark lines. In Fig. 5 I have drawn the curves which give the intensity of radiation in terms of R_0. The abscissæ represent a and the ordinates:

$$\frac{a}{m(1+a)}+(1-a)\ .$$

Table IV gives the corresponding values of a and β.

TABLE IV

α	β	α	β
0.1	0.0101	0.6	0.5625
0.2	0.0417	0.7	0.9608
0.3	0.0989	0.8	1.7778
0.4	0.1905	0.9	4.2632
0.5	0.3333	1.0	∞

In applying the results obtained, it should be remembered that m defines the "radiation-gradient," which depends not only on the "temperature-gradient," but also on the wave-length. The same increase in temperature will cause a greater radiation-gradient at the violet end than at the red end of the spectrum, and at comparatively low temperatures the radiation-gradient may in the violet be enormously larger than the temperature-gradient. Hence we conclude that with moderate increases of temperature toward the inside of a gas, the lines of a spectrum which have a shorter wave-length are much less likely to be bright than those of longer wave-length.

9. It may help the reader to draw the proper inferences from the preceding results if an elementary demonstration is given showing how bright line spectra are formed in an infinitely thick layer of incandescent gas, which, when the temperature is uniform, should, according to the ordinary theory, give a spectrum identical with that of a black body at the same temperature. In Fig. 6 let an observer look from E at a mass of gas giving out two homogeneous radiations λ_1 and λ_2, differing very largely in their emissive and absorptive powers κ_1, and κ_2 The wave-length λ_1 being that for which the emissive power is great, will chiefly be due to the radiation of a thin layer $L_1K_1K_2L_2$, because waves of the same wave-length coming from behind will be strongly absorbed by it. On the other hand, the vibrations of small emissive, and therefore small absorptive power will be due to the radiation of a much thicker layer. Neglecting in the first instance the loss of light due to scattering, we may draw H_1H_2 so that the layer $L_1H_1H_2L_2$ sends out a total intensity of waves, λ_2 representing the same fraction of the radiation of a black body of the same temperatures as does the layer $L_1K_1K_2L_2$ for

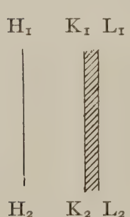

Fig. 6.

the wave-length λ_1. It is well known that whatever be the emissive powers, an indefinite increase in thickness will ultimately give the radiation of a black body. Now, introduce scattering in addition to the absorption. The wave-length λ_1 will not be much affected by scattering, as the light which leaves the gas has only traversed a small thickness of it. On the other hand, the wave-length for which the emissive and absorptive powers are small, being due to the radiation of a thick layer, will be much more weakened by the light scattered, and returned backward. Hence while, in spite of the scattering, λ_1 still shows an intensity nearly equal to that of the black body, the intensity of λ_2 is less. Consequently the radiation will be the stronger, the stronger the emissive power, and hence the gas gives a bright-line spectrum.

In this reasoning it has been supposed that the scattering is of the nature of that due to small bodies and is not a phenomenon primarily dependent on absorption. In the latter case it might be argued that the scattering might be stronger for the wave-length λ_1 in the same proportion as the emissive power is stronger. It is quite possible that a portion of the molecular scattering is selective in character, and, so far as this portion is concerned, our investigation does not apply, without more detailed consideration.

10. I may, in conclusion, briefly indicate the bearing of the results obtained on some problems of astrophysics. It has been shown that a spectrum of bright lines may be given by a mass of luminous gas, even if that gas is of great thickness. There is therefore no difficulty in explaining the existence of stars giving bright lines. The essential criterion which separates the bright-line emission from the dark-line absorption lies in the temperature-gradient of the luminous gas. If the increase of temperature toward the inside of a star is small, bright lines will appear, while the absorption spectra observed in the majority of cases accompany a more rapid variation of temperature. The temperature-gradient is chiefly regulated by the gravitational force, and a star in the early stages of condensation will therefore be in the condition most favorable for the bright-line emission. If the light is but feebly absorbed, so that we can look into considerable depths of the star, it may be possible that the outer regions contribute bright lines, while the hotter inner portions show absorption lines.

The possibility of the simultaneous presence of bright and dark lines of the same element, e. g., of hydrogen, is also strongly indicated by our theory. The matter has already been discussed in sections 7 and 8. The conditions under which the equations of sec. 8 have been deduced are more likely to apply to stars than the conditions of the problem as discussed in sec. 7, and as pointed out at the end of sec. 8, the lines of smaller frequency are those most liable to appear as bright lines. This agrees with the observed facts. The simultaneous appearance of bright lines of smaller and dark lines of greater frequency, has however, also been observed in cases where it is difficult to imagine that scattering plays an important part. I refer to Professor Hale's observations[1] on the spark-spectra observed in liquids. The proper explanation of these and similar observations suggests itself at once, if it is considered that the essential part of the effect of scattering lies in the diminution of the intensity of the continuous background. This diminution is not called for when the body giving the continuous spectrum has not infinitely great thickness and radiates with an intensity less than that belonging to a black body. Putting $s=0$ in (12), we obtain the ordinary equation for the radiation of a body sending out light of intensity S, which before reaching the observers traverses a body which is at a temperature for which the completely black radiation is E, viz.:

$$R=E+(S-E)e^{-\kappa t} .$$

For $\kappa=0$, we have

$$R_0=S .$$

Hence the question of brightness or darkness for a particular wave-length depends on the sign of the quantity

$$R-R_0=(E-S)(1-e^{-\kappa t}) ,$$

and this depends entirely on the question as to whether $E-S$ is positive or negative. If S is the radiation due to a black body at a higher temperature than that of the absorbing body, $E-S$ is necessarily negative and an absorption line will appear. If the radiation S is not that of a black body, but, e. g., a radiation reduced by the same quantity in the red and blue, or even reduced in the same ratio, the peculiar dependence of the radiation curve on temperature and wave-

[1] *Astrophysical Journal*, **15**, 227, 1902.

length shows that $E-S$ which is now positive when the temperature of the two bodies is equal, keeps positive longer with a diminishing temperature of the absorbing layer when the wave-lengths are long than when they are short. I need not enter more fully into this question, because Professor Kayser[1] has fully discussed it in giving what is practically an identical explanation. On applying Professor Kayser's explanation to the case of stars, we meet, however, with the very serious difficulty that we are obliged to consider the radiation of the continuous spectrum which serves as background to be less than that of a black body, which, on the views hitherto held, could not be the case when the radiating body has a great thickness. The consideration of the effect of scattering as explained by the present investigation removes the difficulty. I differ from Kayser in so far that he considers the existence of bright lines in stars to be an indication of high temperature. The small temperature-gradient seems, on the contrary, to argue more in favor of relatively low temperatures. Discussion on these and other connected matters is difficult, however, owing to our ignorance of the relative values of the coefficient of emission κ for different elements, and for different lines of the same element. We do not even know whether in a series such as that formed by the hydrogen lines κ increases or diminishes toward the root of the series.

The appearance of bright hydrogen lines covered by the dark calcium absorption, as presented by the spectrum of *Mira Ceti*, presents no difficulty according to the views of the present investigation. It only implies that the interior of the star has a temperature-gradient insufficient to reverse the hydrogen lines, and an outer atmosphere containing cooler calcium vapor. I consider it indeed as quite possible that, if we could remove the outer layers of the solar atmosphere, we should obtain a spectrum of bright lines.

This brings me to the second consideration suggested by the previous investigation. The prominent part played by the H and K lines of the solar spectrum in stellar atmospheres may be, to a great extent, due to the high values of the coefficient κ. The experiments of Sir William and Lady Huggins show conclusively that when calcium gas is rendered luminous by the electric discharge under

[1] *Astrophysical Journal*, **14**, 313, 1901.

conditions under which the H and K lines can appear, they are most persistent and are seen even when only very minute quantities of the substance are present. We are justified in concluding from these experiments that the emissive power of H and K is very great. The same may be true of other lines characteristic of spark-spectra, and the appearance of these lines in the stellar spectra must therefore be treated with some caution. If a star in its process of condensation increases the temperature-gradient of its outer layers, those lines will first make their appearance as dark lines which have high values of κ. But I must defer the fuller discussion of this matter to another occasion.

The effect of scattering on the intensity of the continuous spectrum of what we call the photosphere of a star may be considerable. When the radiating layer of a gas is sufficiently cool to admit of the presence of particles of solid or liquid matter, of dimensions large compared with molecular dimensions, the reduction in luminosity would take place fairly equally throughout the range of the visible spectrum. There would consequently be no great alterations in the relative intensities of red or blue, and we could obtain a correct idea of the temperature of the radiating body by a thermal comparison of the intensity of radiation in different parts of the spectrum. But when the scattering is molecular, it is sixteen times as large for the extreme visible violet as for the extreme visible red. Consequently the radiation emitted by a mass of gas under these conditions would show the violet considerably weakened as compared with the red. This opens out the possibility that with increasing temperature the violet portion of the continuous spectrum of a star may diminish in intensity as compared with the red end. As will presently appear, we possess some independent evidence that the photosphere emits less violet light than it should do if it were a black surface, but a closer experimental investigation is necessary before this can be definitely established.

I consider that for this purpose the careful investigation of the distribution of intensity in the solar spectrum is a matter of urgent importance. It would be necessary, however, for a satisfactory solution of the problem to measure the intensities everywhere in the intervals between Fraunhofer lines, or, at any rate, to select portions of the spectrum where no prominent Fraunhofer lines are situated.

s is done, we risk that the violet portion of the spectrum w too small an intensity, merely because it contains a greater f Fraunhofer lines.

ss of light by scattering in the solar atmosphere renders it for bright lines to appear which are due to vibrations in the ers, though the temperature at these layers may be less than ich supplies the continuous spectrum. If the scattering is nt, its effect may be to obliterate the Fraunhofer line without converting it into a bright line. It is necessary, however, kind of law should exist as to which of the Fraunhofer lines rated. The two striking facts to be explained are the absence ltra-violet portion of the hydrogen series and the absence of m lines. In both cases the lines appear with considerable y in the so-called chromosphere, and in the flash-spectrum at the beginning and end of total eclipses. With regard to lrogen series, observations on stellar spectra and laboratory nents which have already been quoted, would have led us to ct that the ultra-violet lines would be more easily reversible than ss refrangible lines. If the Sun forms an exception, it seems to ate that the violet part of the continuous spectrum is reduced in sity relatively to the red portion, and that this reduction is not a temperature effect.

his consideration strengthens to some extent the idea that the parative weakness of the ultra-violet radiation in solar stars is due to a diminution of temperature. As already mentioned, molecr scattering in the photospheric region might account for the mparative poverty of the more rapid vibrations.

The behavior of helium cannot be due to the same cause, as none of its lines have been seen reversed in the solar spectrum. The correct explanation is, I believe, to be found in this case in the great height to which helium is found to rise above the photospheric layer. The previous investigation has shown that a bright line is more likely to appear when the product of the coefficient of scattering and the thickness of the absorbing layer is large. This may be caused either by a great coefficient of scattering or by a great thickness of the absorbing layer. It is true that this reasoning should apply equally to hydrogen and the metals which rise as high as helium, and I believe

that it does apply. The absence of some of the hydroge
the solar spectrum has already been noted. That the red
lines can be seen is no doubt a consequence of the fact that
exists in much greater quantities than helium, for it should
that the helium lines are not bright, but only insufficiently d
observed.

This comparative weakness of some Fraunhofer lines w
very prominent in the flash-spectrum, and are probably du
high temperature of the portion of the solar disk emitting th
spondent radiation, has been commented upon by Mr. F
whose explanation I consider in the main to be correct. A
further discussion of some points of detail may be desirable,
ter is independent of scattering, and lies therefore outside t
of this communication.

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THE REVISION OF ROWLAND'S SYSTEM OF STANDARD WAVE-LENGTHS[1]

By LEWIS E. JEWELL.

In considering the desirability of revising Rowland's system of wave-lengths, and of changing to Michelson's absolute values, it is well to consider carefully what were the probable sources of error entering into the determination of Rowland's or Bell's absolute values, Rowland's "New Table of Standard Wave-Lengths," and Rowland's "Preliminary Table of Solar Spectrum Wave-Lengths." It is also desirable that we should consider what work bearing upon this subject has been done since these tables were constructed, and what material has been accumulated capable of furnishing a basis for more accurate tables; and what work it is desirable to do in the near future, in order that the whole subject may be placed upon a satisfactory basis, with the least friction and the least expenditure of energy. In the discussions which have been in progress for some time regarding the corrections to be applied to relative wave-lengths, and the relations between *solar* and *metallic* lines, there are some very important factors which have been almost completely ignored. In the first place, it is well to consider the various errors to which the wave-lengths of lines in the various tables published by Rowland were subject.

The absolute values of wave-length were derived from determinations by Bell, influenced in a measure by determinations of other observers. These were determinations of the wave-length of lines in the solar spectrum, and were corrected, approximately at least, for temperature and air-pressure. Since then better values for the refraction of the air, at different pressures and temperatures, have been determined. The measurements by Bell were also corrected for motion in the line of sight, of the observer's position, as caused by the Earth's rotation upon its axis and revolution around the Sun in a slightly eccentric ellipse.

[1] Paper read in abstract at the Conference on Solar Research, St. Louis, September 22, 1904.

The first determinations of wave-length used in Rowland's early tables were made by Rowland and Koyl, mostly from eye-observations, and were at best only approximate values, and many of the lines taken as standards were of an unsatisfactory character. These measurements were used in the preparation of Rowland's later tables, but were not given much weight, and some of the lines were discarded. Later eye-measurements of relative wave-length were made with both the concave and plane gratings by Rowland and Crew, and afterward by myself from photographic plates taken by Rowland with two or three concave gratings of different values for the grating space. These photographs were upon very fine-grained plates, and the definition in general was very good, but, except in a few cases, no data were given from which the corrections to be applied for temperature and pressure of the air could be derived. Also in the eye-measurements no corrections of this character were made. Rowland himself did not pretend that the measurements were accurate to less than one-hundreth of an Ångström unit, and, such being the case, he had little patience with the idea of making these small corrections; although it is likely that they were responsible for many errors, both systematic and accidental, in his tables, which at times might have been rather greater than one-hundredth of an Ångström unit.

Having made practically all of the measurements from the photographic plates, and the calculations in the work of reduction, I can speak more positively regarding them. They consisted, for the greater part, of two groups of plates, nearly all taken by Rowland, upon fine-grained emulsions prepared by himself. The first set comprised eighteen plates, 14 in. (35 cm) long by 1⅞ in. (4.8 cm) wide, of overlapping spectra for the determination of relative wave-lengths by the method of coincidences, and consisted of a middle strip containing a portion of the solar spectrum in some particular order, and on each side of it strips of a portion of some overlapping spectrum of another order. These were taken by the aid of a shutter which in one position allowed the middle spectrum to reach the photographic plate, and when the shutter was rotated allowed the spectrum of the outside strips to reach the plate, the middle strip being then covered up by the shutter. Rowland was in the habit of giving one of these strips

two exposures, one both before and after exposing the other strip. He did this under the impression that, if anything happened to the apparatus between the first and second, or between the second and third exposures, the average of the first and third would equal the second exposure. This, however, by no means follows. If the effect that produces the error be of a continuous nature, such as the heating of the grating or slit during the exposure or some such cause, that might be true; but if it were due to the act of turning the shutter in some direction and then back again, or some mechanical movement or jar, this would by no means follow, and the third exposure added to the first might simply introduce an error where there had been none before. Also the first change in the shutter might introduce an error in one direction, and the return of the shutter to its original position might introduce an error in the opposite direction, bringing things back to the original condition; and the first and third exposures might thus very well be coincident, but the second exposure would not be compensated for by the average of the other two.

In photographs taken by myself I have found it better to see to it that the shutter worked easily and then to make only two exposures, turning the shutter and doing everything else to avoid any pressure against the apparatus in any direction, and to avoid jars of any kind to parts of the spectrograph. There is no question whatever but that for such work the shutter should be disconnected from the spectrograph, and made entirely independent in its working, or that the parts should be carefully balanced, work easily, and be operated pneumatically or electrically, so that there can be no displacement due to motion of the shutter or pressure against parts of the apparatus. There is no doubt in my mind that in the plates taken for the measuring of coincidences errors of this kind did probably occur, and at times may well have amounted to considerably more than one-hundredth of an Ångström unit. It is quite possible that the errors arising might be such as to cause the lines of the second exposure to be always shifted in a given direction with respect to the other two; and the errors might possibly differ as the camera of the spectrograph was moved to different portions of the spectrum, for even a shift in the position of the observer will cause some variations.

In photographs containing solar and metallic arc-spectra upon

the same plate, the solar spectrum was usually taken in the middle, and the arc spectrum outside. Some of these plates were taken by Rowland, and some of them by myself under Rowland's direction; but scarcely any of them contained data for the determination of motion in the line of sight, or for correcting for atmospheric pressure and temperature, where lines of different orders of spectra overlapped. Another remarkably fine set of plates of the solar spectrum alone were taken by Rowland for making his "Photographic Map of the Solar Spectrum;" but only one of them was used in these measurements, and scarcely any of them had data marked upon them.

The measurements upon both sets of plates mentioned were made by myself, nearly all of them upon a dividing engine constructed by Mr. Schneider under Rowland's direction. The screw of this dividing engine was carefully made by Schneider, and is remarkably free from errors, but the attached microscope was unsatisfactory. The definition of the microscope was not perfect and the field not flat; also some other parts of the dividing engine were not entirely satisfactory. The definition of the plates for coincidences of overlapping solar spectra for the determination of relative wave-lengths were, in general, fairly good, and some of them excellent. The plates for the coincidence of solar and metallic lines were, some of them, good, some bad, and others indifferent. Practically all of them were devoid of data for corrections. One source of trouble was experienced with photographs taken upon thick plates of uneven thickness from the varying focus of different parts of the plate and consequent parallax. Adjustment was made to avoid the trouble as far as possible, and later on means were adopted for nearly getting rid of the trouble. There was, however, always some parallax from curvature of the field of the microscope, but the trouble was avoided and allowed for, as far as possible. The plates for comparison of solar and metallic spectra were 19 in. (48 cm) long by $1\frac{1}{4}$ in. (3.2 cm) wide, and bent to the focal curve of the grating.

Notwithstanding the difficulties mentioned, measurements made upon good lines could, in general, be relied upon to two or three-thousandths of an Ångström unit, and some good lines to one-thousandth of a unit.

All measurements of relative wave-length where lines in different orders of spectra, or solar and arc-spectra, were compared, were subject to the uncertainties due to motion in the line of sight and changes of wave-length due to air-pressures and temperatures, which were not allowed for. Also a few plates were of a very unsatisfactory character, but were used because no others were available at the time.

All of these causes produced errors in Rowland's published wave-lengths which were not allowed for in any way. Also I had discovered a systematic difference in the wave-length of lines in the arc and solar spectra, but Rowland could not be convinced that the difference was due to any cause other than a disturbance of the apparatus between the exposures for arc and solar spectra; and, as a consequence, he had the displacements for different lines upon a given plate averaged up, and applied this as a correction to the arc wave-lengths, to bring them into agreement with the corresponding solar wave-lengths.

This matter has since been thoroughly investigated by myself, and the cause of this difference in wave-lengths determined to be mostly motion in the line of sight of the matter in the Sun's atmosphere producing the absorption lines of the solar spectrum, and to a small extent to a difference of pressure in the atmosphere of the Sun and the electric arc.

For Rowland's "New Table of Standard Wave-Lengths," published in 1893, these measurements were used, together with all previous observations available, and weighted according to their probable accuracy. Then the results were arranged and worked over by Rowland, who introduced certain empirical corrections, where he deemed them necessary, and thus was constructed the table known as Rowland's "New Table of Standard Wave-Lengths." In 1896 Rowland published in the *Memoirs of the American Academy of Arts and Sciences* an extended account of the methods used by him in the construction of this table.

Later I measured up the complete solar spectrum upon Rowland's plates which were used for the production of "Rowland's Photographic Map of the Solar Spectrum." These plates have already been referred to as of particularly good quality.

Considerable difficulty was experienced during these measure-

ments because of Rowland's ideas concerning the necessary accuracy of such measurements, and the desirability of measuring all of the lines in the spectrum. Rowland at that time was not much interested in line-of-sight work, and, in fact, work of that kind was not far developed at the time, and he saw no need of an accuracy greater than was sufficient to identify solar with metallic lines, particularly as he did not consider the wave-lengths of the lines in his "New Table of Standard Wave-Lengths" to be more accurate than one-hundredth of an Ångström unit. Also he did not favor the measurement of the very faint lines of the solar spectrum which were difficult to see, and, in fact, he disbelieved in the existence of many of them. He also disapproved of the measurement of more than one, or at the most two, standard lines at each end of a set of measurements, in order that measurements made at different times might be properly connected, saying that an accuracy greater than one-hundredth of an Ångström unit was entirely useless where the measurement of all of the solar lines were concerned, as the standard lines did not have an accuracy greater than that. Upon these points we were not in agreement at all, and as a result a sort of compromise was arrived at.

Before the measurements were undertaken, Rowland had me take a series of photographs of the solar spectrum upon commercial photographic plates which were rather coarse-grained, and as a consequence many faint and fine lines were obliterated. This he seemed to think a desirable feature, but another important consideration was that these plates were upon the same scale as the dividing-engine screw, and all of a uniform scale, whereas neither was true of the map plates. It was only when he was convinced that the uncertainties of interpretation in the case of double and multiple lines, and the difficulty of measurements in general, would require a longer time to measure the lines upon these plates than the clean, sharp lines upon the fine-grained map plates, that Rowland consented to discard them, and have the measurements made upon his remarkably fine map plates. I had also discovered a method of reducing the measurements which required very little more work than the plates made to scale.

Finally these plates were measured with some few of the most difficult faint lines omitted, but with their existence and their approximate positions indicated. Some of these lines have since been

measured, and the measurement of the others will present little difficulty. The lack of measurements upon a greater number of good standard lines was perhaps the greatest defect of this complete table of solar lines. Of course, the standards were measured along with the other lines, but upon plates containing hundreds of lines, and in some cases two or three thousand lines, they could not all be measured at one sitting; and it was the measurement of more than one or two standards where the different sets of measurements overlapped, to which Rowland objected. These defects can be remedied, however, without much difficulty by remeasuring at one setting, not only the lines taken as standards, but other good clean lines upon these plates. It is the intention to do this as soon as possible, and also to measure the omitted faint lines.

Notwithstanding the difficulties encountered in the making of this table of the complete solar spectrum, known as "Rowland's Preliminary Table of Solar Spectrum Wave-lengths," the wave-lengths not only of the standard lines, but also of most of the good lines in the spectrum, are probably more accurately given than the wave-lengths of the lines in the "New Table of Standard Wave-Lengths."

Later I became interested in the subject of the spectroscopic determination of the rotation period of the Sun, and especially in the question as to whether the period of rotation varied with the elevation above the Sun's surface. This investigation was undertaken largely as a result of the discovery that a line in the solar spectrum had a somewhat composite, and in a measure a complicated, structure; the different portions of shaded lines being produced by absorption at different heights in the solar atmosphere. This investigation was carried on for more than a year, and a great many photographs containing the comparison spectra of the opposite limbs of the Sun, or of one limb and the center of the Sun's disk, were taken. This work was mainly confined to the ultra-violet and violet portions of the spectrum between λ 3700 and λ 4200; but some few plates were taken from the extreme ultra-violet to the yellow and orange parts of the spectrum.

This work was done with the utmost care, and also many sets of eye-measurements were made. These eye-observations included measurements of certain lines in the yellow portion of the spectrum,

near the D lines, which are due to water-vapor in the Earth's atmosphere, and have proved to be remarkably accurate, the water-vapor lines serving as an excellent check upon any possible motion of the apparatus during the observations. Also comparisons were made of a number of metallic with corresponding solar lines, using both the naked arc, and the arc under various pressures. These observations have proved to be very satisfactory, more so than similar measurements upon photographic plates. Many photographs of arc and solar spectra have also been taken, in which all necessary data for corrections have been included.

In the reduction of observations for the determination of the rotation period of the Sun, it was soon found necessary to determine, as accurately as possible, the relative wave-lengths of an entirely new set of standard lines throughout that portion of the spectrum included in the investigation. Some of the standard lines included in Rowland's table were found to be of an unsatisfactory character, and the relative wave-lengths of all of them were found not to be sufficiently accurate for my purposes. The lines which I selected (some of which were the Rowland standard lines that were of good character, or particularly useful for other reasons) were carefully chosen for their sharpness, in both solar and arc-spectra, or for their theoretical interest, as indicated by the investigations mentioned.

The plates taken for the determination of the Sun's rotation period have been carefully measured, all of the better plates in reversed direction as well as direct, and a few of the most important plates have been measured twice both ways. A considerable portion of the work of reduction has been made, but as there were over a hundred plates measured with over a hundred lines upon most of them, and considerably more than that upon a few of them; and as the lines occurred upon both a central and the two outside strips, requiring two sets of measurements, both direct and reversed, the measurements and the necessary work of reduction required a great deal of time. In addition to this, many plates having both arc and solar spectra together were measured, and also many plates having only the solar spectrum.

Besides the plates mentioned, there are a considerable number yet which it is desirable to measure, and it is important that Rowland's

map plates should be gone over again, and all of the selected lines mentioned, occurring upon them, should be carefully measured in both directions. This has been done for some of the plates, but should be done for all of them; and the plates containing arc and solar spectra in the other regions of the spectrum should be measured so as to have an unbroken series of selected lines throughout the entire range of the spectrum. When this is done, the relative wave-lengths of a large number of carefully selected lines in both solar and arc-spectra will have been determined with an accuracy considerably greater than that found in present tables. Moreover, the motion of ascent or descent in the Sun's atmosphere, and the pressure of the Sun's atmosphere where the absorption producing the solar lines takes place, will have been determined for many of the lines and data obtained for determining it approximately for all of them. Much of the work of reduction has already been done for the plates measured, but, as I have had no assistance of any kind, and for the past few years the pressure of other work has prevented my finishing it, there is a great deal to be accomplished yet, but it will be done as soon as possible.

When this work is completed, there will be available a set of carefully selected solar lines whose relative wave-lengths are as accurately determined as is possible at present, and also the wave-lengths of the corresponding arc and spark-lines. The various relations between them will have been determined as well as conditions admit, and it is also expected that the intensities of the lines will have been determined upon a rational system depending upon accurate measurements or comparisons. The basis of the system of comparisons is the varying intensities of the first line in the tail of the a group due to oxygen in the Earth's atmosphere ($\lambda = 6287.953$); and the scale of intensities used is a quantitative one easily reproduced at any time. The actual comparisons, however, are to be made by the use of a photographic scale constructed by a method which has proved satisfactory in actual use. This will require a little, but not much, experimental work, and the actual comparisons are yet to be made; but measurements already made by this method have shown it to be entirely satisfactory.

All of the work mentioned can be accomplished without much

difficulty, and when done it should be based upon the best determinations of absolute wave-lengths available.

Although without doubt Michelson's determinations of absolute wave-length are more exact than any others, it would be desirable to have them repeated by other observers with somewhat different apparatus, and it might also be well for Michelson to repeat his measurements under somewhat different conditions.

It might also be desirable to make absolute determinations of wave-length with larger and better gratings than have ever been employed heretofore for that purpose. If used with a parabolic reflector and a flat mirror in such a manner that the parabolic reflector both collimates the light and brings it to a focus, the flat grating could be made to possess advantages not had by gratings with collimators and objectives; as the focus for overlapping spectra would be identical, and photographic plates could be used in the work.

The grating should be ruled so as to avoid, if possible, errors affecting measurements by careful selection of the ruling diamond and its adjustment; and, if large gratings are made for this purpose, an effort should be made to eliminate to a greater degree than heretofore the periodic and other irregularities of ruling. I believe that this can be done.

The grating method, if it can be used with better and larger gratings, and the other parts of the apparatus better than used heretofore, has many advantages not possessed by the interferometer, in that sharp lines in both arc and Sun can be used, with which better comparisons can be made than with the cadmium lines used by Michelson, which in the arc are not so satisfactory as many other lines. Also photography can be used, and absolute determinations be made in the ultra-violet as well as in the visual spectrum.

More than one large grating should be used, and measurements should be made on both sides of the normal, with each of them. Moreover, "freak" gratings should not be used, but only gratings so ruled that the spectra are symmetrical. Such gratings can be made, and no others should be used for the purpose.

It seems to me that, although it is desirable to have more accurate determinations of relative wave-lengths than are at present available, and also desirable that they be based upon the most accurate absolute measurements which it is possible to make, it would be a serious mistake to make any change now, without having the matter more

thoroughly threshed over than it has been so far; so that what is finally adopted by scientific men will not in a few years be in need of adjustment. Also it seems to me that the set of selected lines which has been mentioned might be made the basis of a set of standard wave-lengths, with the addition of other lines, principally arc or spark-lines, which in various researches have proved to be useful for reference purposes. The relationships between the solar and corresponding metallic lines should all be determined as accurately as possible. Thus we should have a working set of standard lines whose wave-lengths are given for both solar and arc or spark-spectra, with their various relations to each other, and their relative wave-lengths sufficiently accurate for all astrophysical work likely to be done. Furthermore, a specially selected series of some twenty-five or fifty lines scattered throughout the spectrum, which are of good character in both solar, arc, and spark-spectra, should have their relative wave-lengths determined with the utmost possible accuracy with one or more concave gratings, of longer focus, larger size, and better quality than heretofore used for that purpose. These gratings should be at least of thirty or forty feet radius, and be mounted in a thoroughly satisfactory manner, in a place where the work can be done without interference from street traffic or other such troubles. The wave-lengths of this comparatively small number of lines should be thoroughly tied together by the method of coincidences. Two or three gratings having different values for the grating space should be used, the work done by photography, and the measurements made by a dividing engine with an accurate screw made for the purpose. The concave grating possesses advantages for such work not possessed by any other instrument, but the lines in the visual position of the spectrum should also be determined by the interferometer, both as a check and because it will probably give more accurate results in the visual spectrum than the grating. But dependence should not be placed upon the one form of instrument, until results with both have been obtained under the best possible conditions, and then carefully compared with each other.

Finally, the wave-lengths of the few lines referred to, which can be called standards of reference, should perhaps be made to depend upon absolute measurements by interferometer methods, of the red cadmium line, or a few other lines measured in the same way.

How accurate the absolute measurements can be made, it is difficult to say; but the relative wave-lengths of the standards of reference can probably be measured to considerably less than one-thousandth of an Ångström unit. The relative wave-lengths of lines in the working table can probably be made accurate to nearly one-thousandth of an Ångström unit for the better lines, while the others should not be much more in error.

When these sets of standard lines are placed upon a satisfactory basis, the measurements of the wave-lengths of all of the lines in the solar spectrum can be readily reduced to these new values and the few omitted lines added. However, some new plates should be taken in the ultra-violet spectrum above λ 3100 extending as far as possible, and be carefully measured, since Rowland's and other plates of the solar spectrum in this region are unsatisfactory. These photographs should be made on plates as little sensitive as possible to green and yellow light, and with a grating free from diffused light. The photographs should be taken at a station having a considerable altitude above sea-level.

Plates in the extreme red, as far as possible to photograph, should also be taken, or Higgs' original negatives should be measured in the same manner as Rowland's map plates have been.

Also all estimates of intensity should be reduced to the rational system referred to. The full table giving the wave-lengths, etc., of all the lines in the solar spectrum can then be published with the corrected identifications.

All of this work cannot be done in a day, and it cannot all be done by one person; but it seems to me that it would be a mistake to make any radical changes in the wave-lengths of lines until this work has been done as far as possible; and it ought not to take very long to accomplish this result, if it is gone about in the right sort of way.

In the meantime a table can be constructed and published, giving the necessary factors for reducing the wave-lengths in Rowland's published tables, to the absolute values determined by interferometer methods; but as Rowland's standards are not entirely satisfactory in some other respects, any final change from his present system should be avoided until a better table of standards can be published.

Johns Hopkins University,
Baltimore, Md., September 1904.

THE BRUCE PHOTOGRAPHIC TELESCOPE OF THE YERKES OBSERVATORY

By E. E. BARNARD

My experience at the Lick Observatory with the Willard portrait lens impressed me with the importance of that form of instrument for the picturing of large regions of the heavens.

That lens, which was purchased at second hand from a photographer in San Francisco, was made for, and originally used in, taking portraits—from which fact its name has come. These large short-focus lenses were necessary in the days of wet-plate photography to gather a great quantity of light and to give a brilliant image to lessen as much as possible the time of sitting. But when the rapid dry plates came into use these lenses were no longer needed, and much smaller, more convenient, and less expensive lenses took their place. The great light-gathering power for which they were so valuable in the wet-plate days make them specially suitable for the photography of the fainter celestial bodies. They were made on the Petzval system and consisted of two sets of lenses, from which fact they are also called "doublets." In this paper I shall refer to them mainly as portrait lenses, as that name appeals more directly to me.

The main advantage of the portrait lens lies in its grasp of wide areas of the sky and its rapidity of action—this last result being due to its relatively short focus. The wide field makes it specially suitable for the delineation of the large structural details of the Milky Way; for the discovery and study of the great nebulous regions of the sky; for the investigation of meteors and the determination of their distances; and especially for the faithful portrayal of the rapid changes that take place in the forms and structures of comets' tails. There is other and important work where this instrument has shown its special adaptability; viz., in the discovery of asteroids and comets and variable stars; and when it becomes possible greatly to extend its field of view without lessening its rapidity, it will be of the greatest value in the study of the zodiacal light and the gegenschein—two

mysteries that perhaps for their explanation are only awaiting such a photographic investigation.

The portrait combination is not intended in any way to compete with the astrographic telescopes, or with any of the larger photographic refractors or reflectors. It must be considered as supplemental to these, because their limited field confines them to small areas of the sky. There is a great and valuable work for these larger telescopes, however, in the accurate registration of the places of the stars, for parallax, and, in the reflector, for depicting the features of the well-known nebulæ, etc.

There is, I think, however, a question as to the most advantageous size for a portrait lens, and I have believed that the best results can be obtained with an instrument of moderate size; or, in other words, I believe that a portrait lens can be made too large to give the very best results, just as it can be too small. It is also true that both large and small portrait lenses are individually valuable. There is a kind of supplementary relationship between them. The small one will do work that the large one cannot do; and the reverse of this is equally true; for though the small one is quicker for a surface—such, for instance, as the cloud forms of the Milky Way present to it—the larger one, mainly on account of its greater scale, will show details that are beyond the reach of the smaller one. Another important fact is that as the size of the lens increases the width of the field rapidly diminishes, and width of field is one of the essential features of the value of the portrait lens.

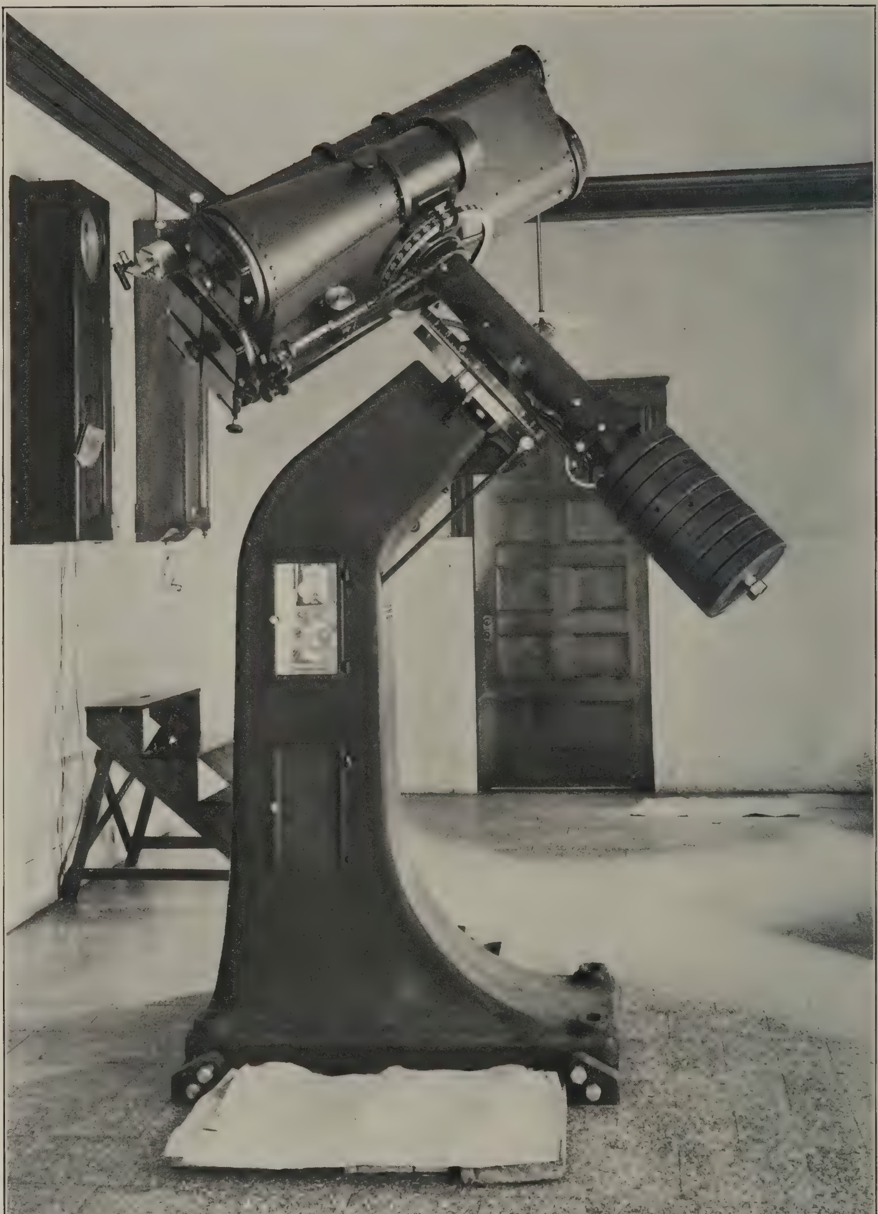
There would, therefore, seem to be a happy mean, when the available funds limit the observer to one lens only.

As a matter of experience, it has seemed to me that a lens of the portrait combination about ten inches in diameter would best serve the purpose of the investigations that have just been outlined.

For several years I had tried to interest someone in the purchase of such a lens, but without success. Finally I brought the matter before Miss Catherine W. Bruce, who had done so much already for the advancement of astronomy. In the summer of 1897 Miss Bruce placed in my hands, as a gift to the University of Chicago, the sum of $7,000 for the purchase of such an instrument and for the erection of a small observatory to contain it.

The instrument and observatory have both been completed and put

PLATE I



Bruce Photographic Telescope in Corridor of Yerkes Observatory

in working order during the present year. The instrument consists of a five-inch guiding telescope and two photographic doublets of 10 and $6\frac{1}{4}$ inches aperture, rigidly bound together on the same mounting. An unusual delay was produced by my anxiety to get the best possible lens for the purpose.

The long exposures demanded in the work of an instrument of this kind require an unusual form of mounting to give an uninterrupted exposure. The mounting of the Willard lens was an ordinary equatorial and was not made specially for it. It did not permit an exposure to be carried through the meridian, except in southern declinations. This was a great drawback since in a long exposure it was necessary to give all the time on one side instead of dividing it up to the best advantage on each side of the meridian.

There were two forms of mounting in use that would permit a continuous exposure. These were (1) the English form of equatorial mounting, which is a long polar axis, supported at each end with the tube swung near the middle; (2) the Potsdam astrographic equatorial, in which the polar axis projects far enough to allow the telescope to swing freely under the pier. Neither of these mountings has appeared to me to be entirely the best form for the purpose.

The focal length of the 10-inch is 50 inches (128 cm); with this short length it seemed that if the pier itself were bent to form the polar axis the telescope could be made to swing freely under the pier in all positions of the instrument. With this idea in view, I went to Cleveland to confer with Messrs. Warner and Swasey on the matter. Mr. Swasey at once took the deepest interest in the proposed telescope, and eventually evolved the scheme that was ultimately adopted in the mounting. The result was entirely satisfactory, and the mounting is, I believe, the best for the purpose that has yet been made.

The next question was the lens, and here is where the delay occurred. It was my wish to get the widest field possible and the shortest relative focus consistent with such a field. This proved to be a problem of the most extreme difficulty. Dr. Brashear, who was appealed to for the optical part, entered heartily into the subject. So earnest was he in his endeavors to fulfil the required conditions that he made at least four trial lenses of four inches' diameter and upward. But my ideal was evidently too high and one not attainable with optical skill.

In the interests of the matter I made a visit to Europe to see if better results could be had there, but, in the end, it proved that Brashear's lenses more nearly fulfilled the requirements than any that I saw elsewhere.

In the meantime Mr. Brashear, with characteristic faith in his skill, ordered the glass and made a 10-inch doublet on his own responsibility. This lens gave exquisite definition over a field some 7° in width and could by averaging be made to cover at least 9° of fairly good definition. Though this did not come up to the width of field originally proposed, it was finally accepted, as it seemed the best that could be obtained.

Dr. Brashear has supplied me with the following information about the ten-inch lens for the present paper.

The glass disks were made by Mantois, of Paris, and delivered to Brashear in May of 1899, and the lenses were completed in September 1900.

"The general construction is that which was first found by Petzval years ago, and has proven itself quite the best where great angular aperture with sharp definition is imperative. The curves have been somewhat modified from our experience in the construction of other lenses—particularly of those made for Dr. Max Wolf, of Heidelberg, Germany. It departs, however, from the ordinary practice of opticians in being corrected for short wave-lengths of light. This would be quite objectless in a camera which is to be used for portraits, but is not without moment in astronomical photography.

"The materials employed were specially chosen for their transparency—the flint being very light and the crown very white. The focal lengths of the front and rear combinations are in a ratio of about 7 to 12, while the focal length of the system is very nearly five times the aperture. The focal length you may find very slightly modified; indeed, it is our custom to balance the inevitable zonal differences of magnification, which difficulty is found the most formidable to all constructors of astronomical photographic objectives."

The accumulation of interest had by this time permitted the purchase of a 6¼-inch Voigtländer lens of 31 inches (79 cm) focus, which had been in commercial use, and a new 4-inch Voigtländer lens with the remarkably short focal length of 7.9 inches, having a focal ratio of less than ½.

As indicated, the telescope is really triple in character, there being

three tubes bound rigidly together on the same mounting—the 5-inch visual telescope for guiding, and the 10-inch and $6\frac{1}{4}$-inch photographic doublets.

The focus of the 10-inch, determined from the photographs, is 50.3 inches (127.8 cm), and the scale is therefore 1 inch$=1\overset{\circ}{.}14$ or $1^{\circ}=0.88$ inch. The ratio, $\frac{a}{f}=\frac{1}{5.03}$, I believe to be the best for the purpose.

In the matter of a guiding telescope the limited means would not permit of anything larger than 5 inches, which is sufficiently powerful for ordinary purposes, though for the photography of comets a larger one would have been desirable. The guiding telescope I used with the Willard lens at Mt. Hamilton was only $1\frac{3}{4}$ inches in diameter. Of course, the question of a double-slide plate-holder was considered; but in a small telescope like this the tubes are so rigidly bound together that such a device is not necessary to insure faithful guiding. Furthermore, for work of this kind the double-slide plate-holder would be seriously objectionable.

The plate-holder for the 10-inch carries a plate 12 inches square, while the one for the $6\frac{1}{4}$-inch carries a plate 8×10 inches.

A high-power eyepiece is used on the 5-inch for guiding in conjunction with a right-angled prism. This is more convenient than direct vision, especially when photographing at high altitudes. The eyepiece has an adjustable motion to the extent of 2° in any direction, thus insuring the finding of a suitable guiding star. This is also valuable in photographing a comet, as it permits the displacement of the comet's head to one side of the center of the plate, thus securing a better representation of the tail.

Two spider-line cross-wires in the eyepiece are used for guiding. They are illuminated by a small electric lamp by the aid of two small reflecting surfaces which throw the light perpendicularly on the wires. The intensity of the illumination is readily regulated. By this means almost the smallest star visible in the 5-inch can be used for guiding purposes.

The illustration will give a better idea of the Bruce telescope than any mere words can do. Indeed, there are very few things about it that need explanation. One feature, however, will not be clear without a description, viz., the method of adjustment for latitude in case the

telescope were removed to a different latitude. It was intended that the instrument should be portable when occasion required, for the purpose of observing eclipses, etc., and for possible transportation to the Southern Hemisphere.

The pier really consists of two parts. Just above the clockroom it separates into two pieces which are bolted together on the inside of the pier, and hence no break appears in the continuity of the pier.

For change of latitude, it is only necessary to insert a wedge-shaped section between these two parts of such an angle that it will produce the required change of latitude. This ordinarily would necessitate only a slight change in the length of the driving-rod which is adjustable. No other means of adjustment seemed feasible.

As it was possible that the instrument might some time go to the Southern Hemisphere, Messrs. Warner and Swasey were asked to insert some sort of gearing that would readily permit of a reversal of the motion of the clock. The device they introduced is extremely simple and efficient. In a couple of minutes' time the motion can be changed from west to east. At the point where the driving-rod joins onto the worm-screw for driving the worm-wheel carrying the telescope, the small gear-wheel which makes the connection can be reversed and placed on the other side of the gear-wheel at the end of the driving-rod; this will reverse the direction of motion of the worm-wheel and hence of the telescope.

The telescope is supplied with fine and coarse right ascension and declination circles, the fine circles are divided on silver and are read by verniers.

The slow motions for guiding are brought down conveniently to the plate-end of the instrument.

For each of the photographic lenses there is an inner tube, with focusing scale, which can be racked back and forth for the adjustment of focus.

For adjusting the instrument in position, the base of the pier rests on two broad iron bars at the north and south with screws at their ends. The upper screws in the picture are for changing the azimuth, while the lower ones push iron wedges that elevate the northern and southern ends of the pier. This latter arrangement seems to be about the only thing for criticism about the instrument. The wedges are

not attached to the screws, and hence if they are pushed in too far they cannot again be drawn back and the other end of the pier must be raised; and if by chance this goes too high, it is necessary to come back to the first wedges and push them higher again. If they were attached to the screws, they could be drawn back again. As the wedges are rather thin, one or two misses of this kind drives them in so that they can no longer act. It would have been better to have had the wedges fastened to the ends of the screws, so that by turning the screws one could either raise or lower the end of the pier. But this is a mere detail that can be easily remedied in future instruments. It is a question if the old method of adjustment in altitude by vertical screws is not a better one than this—certainly it would be preferred to the present arrangement. The pier is very heavy, weighing some 1,200 or 1,300 pounds (550–600 kilos). This great weight is necessary to support the overhanging mass of the telescopes and the top of the pier.

The driving-clock is of Warner and Swasey's regular conical pendulum pattern, which by all means seems to be the best form of driving-clock. It is a beautiful piece of mechanism and performs satisfactorily, though we intend to introduce an electric control for work with it hereafter.

The photograph shows the telescope as it was temporarily set up in the corridor of the Yerkes Observatory.

As will be seen, the design is a new one, and although Messrs. Warner and Swasey have made at least one mounting of this kind (for the Tokyo Observatory) before the Bruce telescope was commenced, it was made from their design for the present instrument, so that the Bruce is the original of this particular form of mounting.

The photograph shows the compact and rigid form in which the tubes are mounted, and it will at once be seen how the combination can swing freely under the overhanging pier.

The instrument was finally finished and placed in position in its observatory in April of 1904. The results so far obtained with it have proved satisfactory and give promise of a useful career.

As I have said, small portrait lenses have their special advantages as well as the larger ones. Where it is possible, it is desirable that two or more lenses should be used on the same mounting, a very

important point being that they mutually verify each other. Duplicate lenses would not seem to be either the most economical or the best arrangement. In that case they would serve only as a verification and could have no other value, unless indeed one of the plates should meet with an accident or be defective—circumstances that would not be of sufficiently frequent occurrence to justify the extra outlay. The best plan would seem to be to have one of the instruments decidedly different from the other so that an independent series of pictures of the same region could be secured on a very different scale. Photographs with these, at the same time that they mutually verified each other, would have other values peculiar to themselves.

The 10-inch and the 6¼-inch, therefore, mounted together, give a very desirable variety in respect to scale, at the same time that the 6-inch is sufficiently powerful to be an almost perfect verification of anything the 10-inch may show. There is plenty of room for other and smaller instruments to be fastened onto the mounting or tubes, and it is intended to utilize this space, especially during periods when meteors are plentiful, or in the case of a bright comet.

The very short-focus Voigtländer lens mentioned is very rapid. It is indeed so rapid that the sky itself photographs with it, which is a serious disadvantage. Under ordinary conditions the sky is more or less whitish, due to the scattering of starlight by dust and moisture in the air; this milkiness strongly affects the plate with a very quick lens such as the one I refer to, and a long exposure is, therefore, impossible; at the same time, for want of contrast the very objects for which such a lens is intended are lost in the general illumination of the plate. To use an instrument of this kind with any success, a pure atmosphere, free from any whiteness, is required. This lens gives a little over one inch, or about 11° or 12°, of perfect definition. Experiments show that plates slightly concave will readily double this amount, and it is hoped some time to use curved plates with it. At present the trouble in using curved plates comes entirely from the difficulty of getting them uniformly coated with the sensitive emulsion. This is a fault that the plate-makers would readily remedy if there were any commercial demand for such a plate that would pay them for their trouble.

In the actual working of the instrument, some few alterations were

necessary, but through no fault of the makers. These changes have been very skilfully made by Mr. Johannessen, the instrument-maker of the Yerkes Observatory, to whom I am very greatly obliged.

The Bruce Observatory is a wooden building of size, 15×33 feet, with the greater length lying east and west. The dome, which is central, is 15 feet in diameter and revolves on 8-inch roller-bearing iron wheels which were supplied by William Gaertner & Co., of Chicago.

In the use of any telescope a wide observing slit is either a necessity or a great convenience. Too often this opening is entirely too small for the telescope used. Besides the inconvenience it produces, such a small opening is often productive of poor seeing.

The large field of the Bruce telescope made a wide opening in the dome a necessity. It was therefore made 4 feet wide, which seems ample for all purposes. The telescope rests on a brick pier, and the observing-room is reached by a small stairway against the inner south wall of the building. Below the observing-room and around the pier is an octagonal hall. This is entered from the outside by a door to the north. The east end of the building consists of one room, which may be called the office or library, leading into the hall just mentioned. The west end of the building consists of two rooms, one of which is entered from the hall, and from this room a door leads into the other, which is a dark room with sink and water pipes.

The octagonal form of the walls supporting the dome conveniently gives space for four closets in the east and west portions of the building. These are very useful, especially the one in the dark room, as it makes a good temporary storage-room for plates that are being used. The two closets in the east room are respectively intended for clothing and for books.

As the observations are often carried through the zenith with this telescope, the floor of the observing-room would need to be very low, or the observer must assume a crouching and uncomfortable position for a portion of the exposure. If the floor were low enough for comfort in this position, the observer would have to be perched upon a high observing-chair for a large part of the time, which would also be inconvenient. To modify these conditions as much as possible,

a couple of small, removable trap-doors are let into the floor where the most awkward position of the telescope occurs beneath where the pier overhangs. The space between the floor and the ceiling of the room below—or the top of the brick pier—is about 15 inches. In the lower position of the instrument one can remove the cover from a trap-door and sit comfortably on the edge of the floor with his feet in the space below and guide with the greatest ease, as a diagonal eyepiece is used. With this arrangement the floor has been placed at a convenient height for the observer in all positions of the instrument, and at most only a small low observing-chair is needed. This is a simple and great convenience in using an instrument of this kind. There is also in the floor on the west side of the pier another and larger trap-door through which the pier can be lowered when it is to be transported elsewhere.

No instrument was available for laying out a meridian when the Bruce Observatory was built. It was necessary, therefore, to find the meridian with the naked eye. As the way this was done may be helpful to others in a similar predicament, I will briefly describe it.

The Central Standard time of the passage of the lower meridian by η *Ursae Majoris* was computed and the watch set to correct time. At a point 400 feet south of the 40-inch dome a plumb-bob was suspended with a fine white cord from the hand. This cord was illuminated by the light from a bull's-eye lantern. At the exact moment the star crossed the meridian, as indicated by the watch, the star and plumb-line were made to coincide with the vertical wall of the tower of the 40-inch dome, and the plumb-bob was dropped, and a thin stake driven vertically into the ground where its point had touched. This stake and the edge of the tower were then in the meridian. On another night, as a check, the process was repeated at a distance of 200 feet. These two vertical stakes were found to be so exactly in a line with the edge of the tower that the eye could detect no difference.

This meridian line was then carried westward by careful measurement to the proposed site of the Bruce Observatory. As a further check, after the pier had been built, a string was suspended, with a weight on the end, from a support above the pier and at the computed time of the transit of the Sun the shadow of the string was traced on

PLATE II

THE BRUCE PHOTOGRAPHIC OBSERVATORY OF THE YERKES OBSERVATORY
April 15, 1904. View from Northwest

the top of the brick pier. So exactly had the pier been built that scarcely any deviation existed between its side and the trace of the shadow. Furthermore, when the telescope was put in position and adjusted, its position scarcely sensibly deviated from the adopted meridian.

A better way to have laid out the meridian at the site of the observatory itself would have been to suspend a plumb-line from a support several hundred feet to the north, with a light thrown on it to make it visible, and to have used it instead of the edge of the tower of the 40-inch dome. This star η *Ursae Majoris* transits the lower meridian at a very low altitude here, which makes it very convenient for the purpose of getting the meridian by the above method.

This small observatory is a beautiful building, as will be seen by the photograph. It is the design of Mr. James Gamble Rogers, architect, Chicago. The style is plain and simple. The body of the building is a light gray, with white trimmings, and the dome is white. The center of the dome is 139 feet west and 394 feet south of the center of the 40-inch dome. It lies between the Yerkes Observatory and Lake Geneva, which it overlooks and which is seen in the background of the picture. The horizon is free in all directions, except an unimportant part cut out by the 40-inch dome. The building is lighted by electricity, and it was intended also to heat it by electricity, but the expense of such heating perhaps makes it prohibitive. The electrical appliances were all put in by Mr. Frank Sullivan, of the Yerkes Observatory.

From the numerous photographs already made with the Bruce telescope I have chosen two pictures of the Milky Way, one of which was made with the 10-inch, and the other with the 6¼-inch. These pictures are both in *Cepheus* and are adjacent regions.

The photograph with the 10-inch is of a great nebula found with the 6-inch Willard lens in the summer of 1893 (see *Knowledge* for January 1894). The center of this object may be taken at the star *B. D.* $+56^\circ.2617$, the position of which for 1855.0 is R. A. $= 21^h\ 34^m\ 29^s.8$; Dec. $= +56^\circ\ 49'.7$. The nebulosity is roughly roundish and is about 2° in diameter. It is broken up with peculiar dark rifts, not unlike those in the Trifid nebula, and involves a group of moderately bright stars. It lies along the boundary of two regions, one

rich in stars and the other comparatively poor. I have previously called attention to this peculiarity of many of these great diffused nebulosities.[1] The sky was not specially suited for photographing such an object and I hope to repeat the exposure under better conditions, and shall expect to show much more nebulosity, as greater extensions are faintly indicated. The scale of this picture is 1 inch $=0^\circ.84$. It is enlarged 1.36 times from the original.

The second photograph, with the $6\frac{1}{4}$-inch, shows the peculiar structure of the Milky Way in that part of the sky. The groundwork here is made up of comparatively small stars with a scattering of relatively bright ones. It is a fair sample of what can be done with the ordinary commercial lens which was never intended for this kind of work. It is very slightly enlarged from the original, and the scale is 1 inch $=1^\circ.8$, or about one-half that of the other photograph. Though the definition at the corners of the plate is poor, from spherical aberration, it was thought best to include these corners, since they carry out the structural details without being seriously offensive.

For many years I have called attention repeatedly to the fact that many of the nebulæ occupy vacant regions as if their existence was in some way the cause of the scarcity of stars. Perhaps the most remarkable instance of this kind is the region of the great nebula of ρ *Ophiuchi* where the nebula is situated in apparently a large hole in the Milky Way, and this hole is connected with a remarkably accentuated vacant lane running from it to the east for many degrees.[2] This peculiarity is also noticeable in the case of the great nebula of *Orion*, where the region occupied by the nebula seems to be vacant of the very small stars that form the general background of the sky in that part of the heavens. Though there are many small stars connected with the nebula, they do not appear to belong to the regular background of the sky there, and perhaps are all intimately associated with the nebula itself.

In reference to these dark lanes and holes, there seems to be a growing tendency to consider them dark masses nearer to us than the Milky Way and the nebulæ that intercept the light from these objects.

[1] See *Astrophysical Journal*, **2**, 350, December 1895.

[2] See *Popular Astronomy* for September 1897 (Vol. **5**, p. 227) for a full description of these features.

PLATE III

N.

NEBULOSITY IN THE MILKY WAY

Center at R.A. = $21^h\ 35^m$; Dec. = $+57°$. October 6, 1904, from $7^h\ 14^m$ to $12^h\ 25^m$ C. S. T.

10-inch Lens. Scale: 1 cm = $0.°33$

This idea was originally put forward by Mr. A. C. Ranyard. Though this may in a few cases be true—for some of them look very much that way—I think they can be more readily explained on the assumption that they are real vacancies. In most cases the evidence points palpably in this direction. In the few cases where the appearance would rather suggest the other idea—and this is mostly in reference to the nebulæ—the evidence is still not very strong.

The 6¼-inch lens does not cover sharply as large a field as the Willard lens, but it must be remembered that the Willard was refigured by Brashear. In the lower left-hand corner of this picture, where the definition is poor, are seen the vacant lane and small nebula shown in Dr. Max Wolf's beautiful photograph reproduced in *Monthly Notices*, **64**, 838. The large nebulous cloud shown in the northwest part of his plate does not seem real. It does not look like nebulosity on the photograph itself, and it is not shown on either the present plate or the one with the 10-inch made at the same time. It must be a defect of some kind. I have been familiar with this vacant lane and small nebula to which Dr. Max Wolf calls attention, since October of 1893. I have a photograph clearly showing them on October 11, 1893.

The relationship of the two present photographs will be seen from the fact that in the picture with the 6¼-inch the small star 0.6 inch from the top and 2.3 inches from the right-hand side is the conspicuous star near the lower right-hand corner of the 10-inch photograph.

Through the deep interest of Professor Hale in the possibilities of the Bruce telescope, we decided, at a discussion of the subject in the past summer, temporarily to transport the telescope to the summit of Mount Wilson (6,000 ft. elevation) near Pasadena in southern California, where Professor Hale has already established a branch of the Yerkes Observatory for solar work. The telescope was therefore taken down and shipped to California on December 5. It is intended to use the lower latitude of Mount Wilson to reach those magnificent regions of the Milky Way in *Sagittarius* and *Scorpio* which are not attainable from the latitude of the Yerkes Observatory, and to secure photographs of them during the coming summer. It is also hoped to utilize the transparent sky of Mount Wilson to photograph some of the great diffused nebulosities that are more or less cut out by the denser air at lower altitudes.

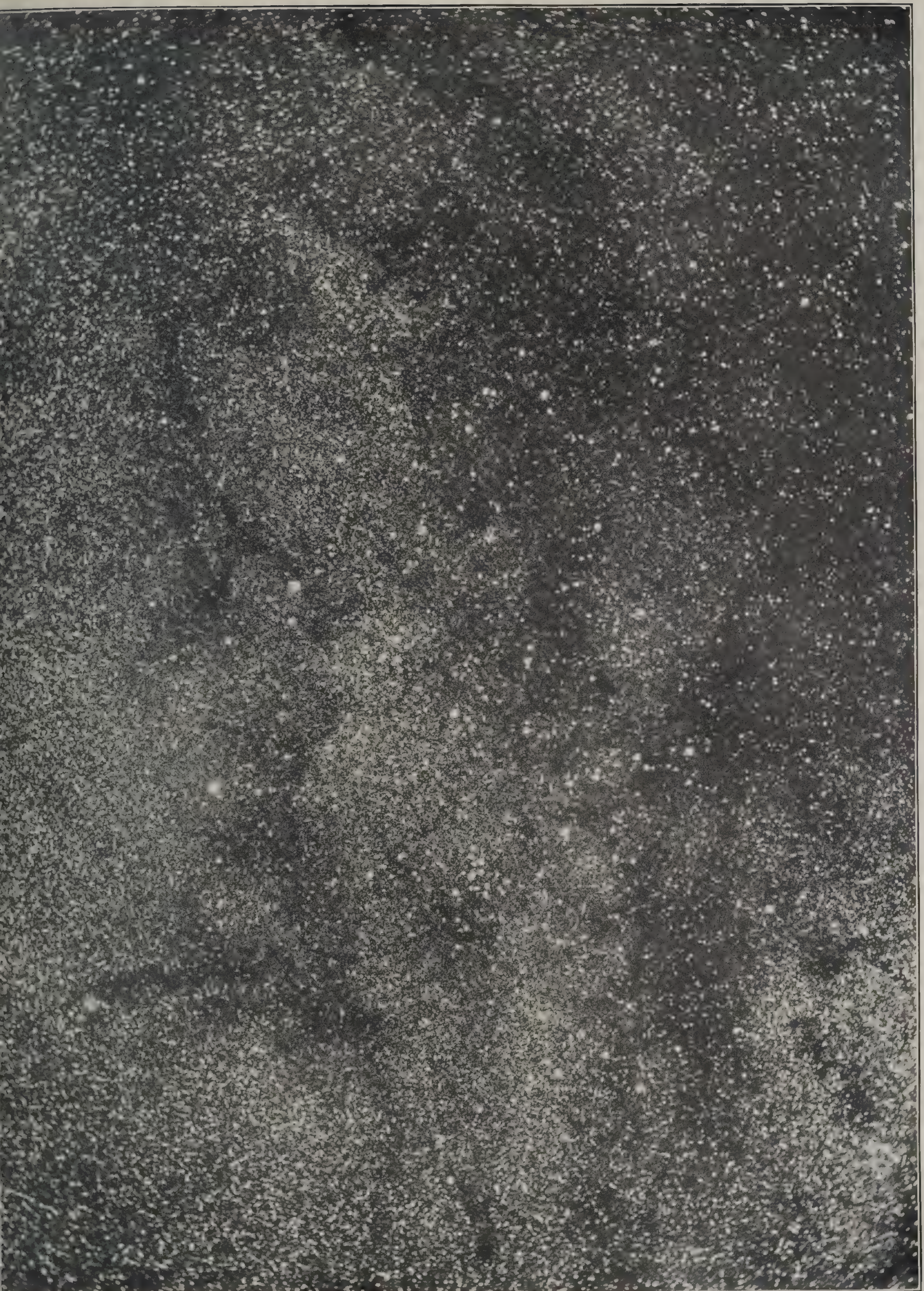
The $6\frac{1}{4}$-inch doublet is soon to give place to a new 6-inch doublet made from the new Jena ultra-violet glass, which is specially suited for photographing the nebulæ. It is expected that this will be finished in time to be used at Mount Wilson. An objective-prism of the same glass and of equal aperture has also been ordered from Zeiss & Co.

The telescope has been in use since the middle of April, until it was taken down in the last of November for shipment to California. In that time some eighty negatives were obtained with each camera, though the season has been unfavorable for work of this kind. One striking feature of these photographs is the number of meteor trails that have been obtained. Nearly a dozen have been photographed. On two different dates two trails were obtained on the plates. The first of these were two bright Lyrids that followed each other closely on April 20. The two trails are almost in a straight line—one coming on the north side of the plate and the other going off to the south. At first glance it looks like one meteor trail interrupted in the middle. On November 15 a fine Leonid trail in *Orion* was obtained. This same meteor was photographed by Mr. Sullivan with a 4-inch camera attached to the end of the 40-inch telescope during the spectrographic observations by Professor Frost. Though the distance between the two instruments was only about 400 feet, there is a decided parallax, from which the distance of the meteor will be obtained.

In conclusion, I wish to express my very deep obligations to Professor Hale for the courtesy and kindness he has constantly shown me throughout all the wearisome time it has taken to get into working existence this valuable gift of Miss Bruce. I am also greatly indebted to Professor Frost for a continuation of these same good services. To Messrs. Warner and Swasey I am most deeply indebted for the interest they have taken in the making of this telescope, and for the fact that the price paid for the instrument has been a secondary consideration with them. They have given more than they have been paid for, and have taken a genuine pride in the work from its beginning. I am indebted to Dr. Brashear for his earnest endeavors to make a lens to fulfil all the requirements that were demanded of it, and for the excellence of the lens he finally produced.

YERKES OBSERVATORY,
December 1904.

PLATE IV



Milky Way in Cepheus

Center at R.A. = $21^h\ 30^m$; Dec. = $+\ 49^\circ\!.5$. September 11, 1904, from $8^h\ 0^m$ to $14^h\ 40^m$ C. S. T.

$6\frac{1}{4}$-inch Lens. Scale: 1 cm = $0^\circ\!.7$

THE SPECTROHELIOGRAPH OF THE POTSDAM OBSERVATORY

By P. KEMPF

Interest in the photography of the Sun in monochromatic light has been decidedly increased by the important results obtained by Hale and Ellerman[1] with the Rumford spectroheliograph, designed by them and used in connection with the forty-inch refractor of the Yerkes Observatory; and it is scarcely to be doubted that the efforts of the American astronomers to enlist more observers in these investigations than have hitherto devoted themselves to them will be successful.

For a number of years the writer has made regular observations with the spectroheliograph—at the Astrophysical Observatory of Potsdam, accounts of which have been given in the annual reports of the observatory in the *Vierteljahrsschrift der Astronomischen Gesellschaft.* A detailed communication as to these observations has, indeed, not yet been made, as it was my purpose to publish the results at the same time. Preoccupation with other work has hitherto frustrated this purpose, but I would now give at least a description of the apparatus and method of observation, since it is presumable that more such instruments will be used in the near future, and hence the description of the experience with the instrument might be of value.

The spectroheliograph used by me is essentially of the form used by Hale[2] on Mount Etna in his attempts to photograph the solar corona. In the first instrument built by Hale the two tubes of the spectrograph formed an angle of 25° with each other. They were rigidly attached to the refractor, and the two slits only were moved by a system of levers, simultaneously and in opposite directions.[3] This form had, as is well known, the disadvantage that the two slits must be given unequal velocities, so that the resulting photographic image was not round, but ellipitical. This defect was avoided in the

[1] *Publications of the Yerkes Observatory*, Vol. **3**, Part I, 1903.

[2] *Astronomy and Astro-Physics*, **13**, 681, 1894.

[3] *Ibid.*, **11**, 407, 1892.

second form, that designed for Mount Etna, by placing the collimator and camera tubes parallel and moving the whole spectroscopic apparatus past the fixed focal image and photographic plate. This form is doubtless the simplest, and, for instruments not too large, the most advantageous, and I chose it on that account for the Potsdam apparatus.

The Potsdam apparatus was constructed by Otto Töpfer and Son in Potsdam, who built the Etna instrument for Hale. Plate V gives a general view of the apparatus, Fig. 1, a drawing of the cross-section, and Plate VI shows the instrument attached to the Grubb refractor of the Potsdam Observatory.

Fig. 1 shows the two adjacent parallel tubes of the spectrograph, the collimator C and the camera K, with the objectives O_1 and O_2 and the slits S_1 and S_2. The tubes are attached at the objective and slit ends to stiff metal plates which form the support for the movable part of the apparatus. These plates are bound together by two strong T-shaped iron bars T, T. The objectives project into an aluminum box which contains the grating G, together with a mirror and a total-reflection prism. These are so adjusted that the beam of light falling on the grating makes an angle of 30° with the optical axis of the camera tube. The two telescopes are also made of aluminum. The tube K is divided at t, and the whole slit part may be removed and be replaced by a much wider conical piece which makes it possible to photograph a longer portion of the spectrum. The junction T is made light-tight by a metal collar.

Objectives and slits are separately movable in the direction of the optical axis. The width of the slit S_1 may be regulated by a micrometer screw which moves one jaw of the slit. On the other hand, the jaws of S_2 open symmetrically, so that the middle of the slit remains in the same place. Furthermore, the whole slit-plate can be moved at S_2 perpendicularly to the optical axis, in order that the slit may be conveniently set upon a given spectrum line. The change of slit-width as well as the movement of the whole slit is effected by keys which can turn the screw heads s, Fig. 1, from outside. The amount of the displacement is read on the ocular scale of a microscope which also, with the help of a total reflection prism, enables the observation of the spectrum through the second slit (Plate V).

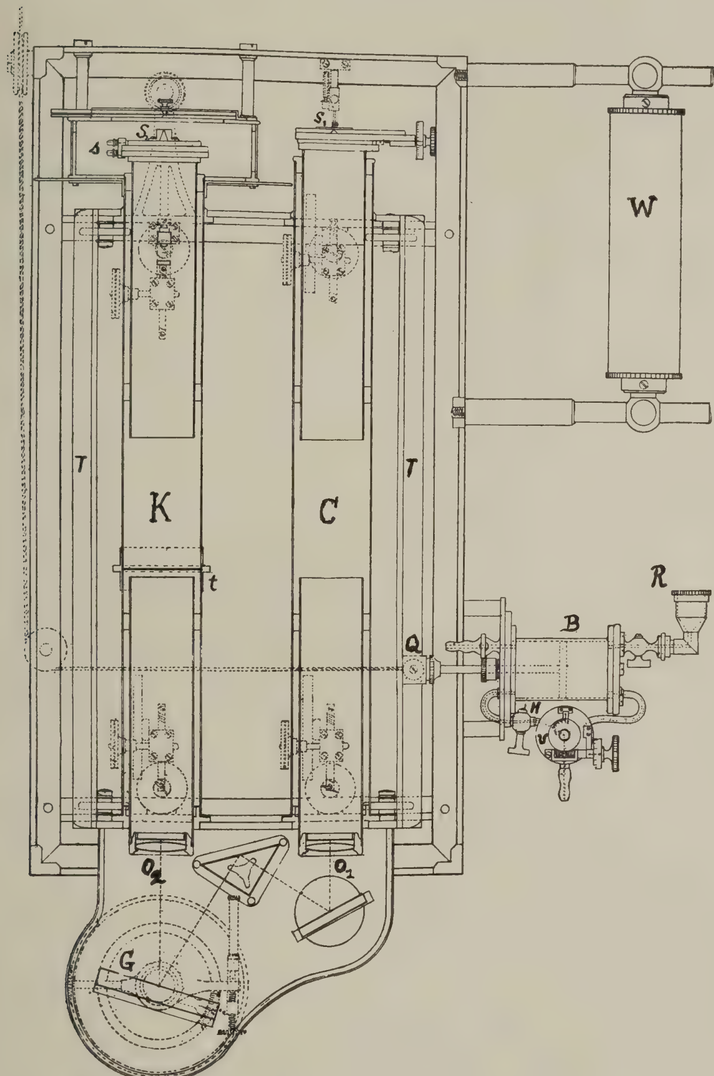


FIG. 1.—Plan of Spectroheliograph.

The motion of the apparatus is accomplished in the following manner: Four right-angle ways are attached to the box-shaped iron frame which incloses the whole apparatus. On these ways run sixteen rollers, which are attached in pairs perpendicular to each

other, to the above-mentioned metal plates (which carry the objectives and slits). The driving is accomplished by a weight which is attached at the two ends of a small cross-piece Q resting upon one of the T-shaped connecting pieces (Fig. 1).

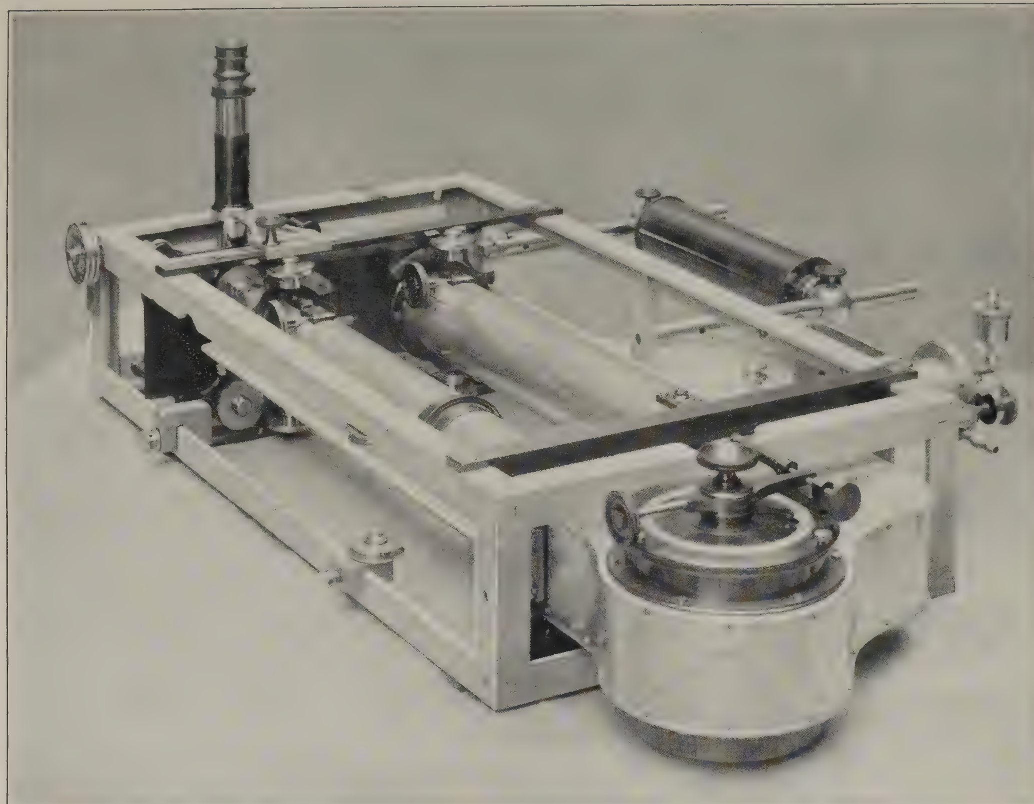
Two cords go from the bar Q over two rollers to a little pulley, and from there as a single cord over a pulley mounted on an extension of the declination axis to a weight (see Plate VI), which may be increased as desired by adding disks.

The motion is regulated by a clepsydra B, whose piston is attached to the same place as the driving-weight. The tube connecting the two ends of the cylinder is interrupted in two places—at H by an ordinary cock and at v by a micrometric cock capable of varying the outflow between wide limits. In order to prevent air from entering the regulator, I had a reservoir attached at R which is kept constantly filled with liquid. While the instrument is not in use the valves are opened so that the water may have free circulation, the drain of water from the reservoir being immediately resupplied. In filling the reservoir Hale's plan of using a mixture of water and 5 per cent. of glycerin was followed, as such a mixture resists severe cold without freezing.

The whole moving mechanism works very smoothly and is wholly free from vibration, so that it may be highly recommended, especially for small instruments.

The manner of attaching the apparatus to the refractor is shown in Plate VI. The collimator lies in the prolongation of the optical axis of the telescope, and in order to balance the camera tube, etc., the counter weight W (see Fig. 1) had to be attached. The disk to which the frame is attached may be rotated in position angle so that the apparatus can be moved in any direction desired. It is most advantageous to keep this motion parallel to the diurnal motion, and then to keep the apparatus unchanged in this position, the deviations from this adjustment being determined at appropriate intervals. The direction of motion of the apparatus is marked on the photograph by the lines traced by small dust particles on the first slit. To provide against the desirable case where all dust particles are removed from the slit, a thin metallic wire is run across the first slit, and it appears on the photograph (Sun's image) as a sharp and easily measurable line. This wire serves also to deter-

PLATE V



THE POTSDAM SPECTROHELIOGRAPH

mine the error of position angle. The second slit for this purpose is opened as wide as possible (in my instrument 3 to $3\frac{1}{2}$ mm) and a photograph of the spectrum is made. Then the apparatus is run a considerable distance, and the driving-clock of the refractor is stopped so that the solar image also moves forward. At the instant when the Sun is again centrally on the slit a second photograph of the spectrum is taken. Measurement of the distance in declination of the wire from the center of the Sun on the two photographs then gives the deviation of the motion of the apparatus from the direction of the diurnal motion.

As previously mentioned, the spectrum is produced by a plane grating, furnished by Brashear, with a ruled surface of 2×3 inches, and about 14,000 lines to the inch. It is undeniable that for the purpose in hand prisms have advantages in many respects, especially as they give less diffuse light than the grating. I was not in position to employ prisms, however, as my eyes are not sufficiently sensitive to violet light to be able to bring the K line with certainty into the slit of only about 0.1 mm width. With the grating the K line in the fourth order, which I use for my observations, coincides with the green of the third order, so that the setting may be made upon a green line, the distance of which from the violet line has been determined once for all.

As to the diffuse light, the camera tube is further furnished with a system of diaphragms which grow constantly smaller from the objective to the slit, keeping diffuse light off the second slit as far as possible. Similarly a diaphragm is placed between the grating and the total-reflection prism. It divides the whole space into two parts and allows the passage of only the light coming through the prism.

The Grubb refractor, to which the spectroheliograph is attached, has a focal length of 3.2 m, and the focal image of the Sun is therefore about 30 mm in diameter. The following dimensions were accordingly chosen for the various parts of the spectroheliograph. The length of the slits and the clear aperture of the objectives is 45 mm, the focal length[1] of the collimator and camera 600 mm. The cylinder of the regulator is 5×8 cm and permits a total motion of the apparatus

[1] The focal length might better have been smaller.

of about 6 cm. The frame which incloses the whole apparatus measures $68 \times 36 \times 13\frac{1}{2}$ cm.

It is clear that an instrument of these modest dimensions cannot give results comparable to those of the Rumford spectroheliograph at the Yerkes Observatory in which the solar image is 18 cm in diameter. In particular it is not possible to bring out the fine structure of the Sun's surface, which the beautiful photographs of Messrs. Hale and Ellerman reveal. All coarser structure may be perceived on our photographs, however, and can be measured under low magnification with adequate accuracy. Unfortunately, it is not probable that any considerable number of instruments with the great dimensions of the Rumford spectroheliograph will be built, so that it is the more to be desired that at least there shall come into use as many instruments as possible of the dimensions described here, which do not involve extraordinary expense.

Potsdam, Astrophysical Observatory,
October 1904.

Spectroheliograph Attached to Refractor

ON THE DETERMINATION OF RADIAL VELOCITIES AT POULKÓVA

By A. BÉLOPOLSKY

In my last article on "Standard Velocity Stars,"[1] I mentioned among other things an error, the cause of which was at the time not clear to me. It was the fact that the light of a star, projected on the slit of the spectrograph by the thirty-inch objective, did not wholly fill the objective of the collimator, but only illuminated one-half of it.

Another error which I was unable to overcome for a long time was that the lines of the stellar spectrum always appeared inclined with respect to the artificial spectrum and, probably for this reason, were never as sharp as the appearance of the artificial lines would lead one to expect.

I first sought the cause of these errors in the spectrograph itself, of which I will now give a few details. The instrument is essentially a copy of Spectrograph III of the Potsdam Observatory. The length of the collimator is 614.7 mm for the setting 10.0; that of the one camera is 605.3 mm (always reckoned from the front surface of the lens) at the setting 13.2; and of the other camera, 413.1 mm at the setting 18. The rays of the spectrum are united as follows by the long camera (A) as determined by Hartmann's method:

Edge of Wedge under Plate Points toward Violet				Edge of Wedge under Plate Points toward Blue			
λ	Setting	λ	Setting	λ	Setting	λ	Setting
400	9.2	430	13.2	406	7.8	438	13.1
410	12.0	438	12.5	414	9.4	444	13.1
414	12.8	444	11.9	420	10.6	450	13.0
420	13.9	450	11.3	430	12.6	454	13.0
426	13.8	454	10.9	434	13.1	...	....
T. = −0°5 C.				T. = −4°0 C.			

The camera setting for wave-lengths between λ 414 and λ 440 changes with the temperature as follows:

[1] *Astrophysical Journal*, **19**, 85, 1904.

T.	Setting	T.	Setting
+0° C.	13.0	+12° C.	12.4
4	13.0	14	12.0
8	13.0	16	11.4
10	12.8	..	....

For the short camera (B) we obtain the following camera settings for different wave-lengths. The first table is for the position with the line $H\gamma$ at the center of the field, and the settings remain unchanged for the range of temperature from $-2\overset{\circ}{.}4$ to $+11\overset{\circ}{.}5$ C. The settings are also given for the cases where the other hydrogen lines are at the center of the field.

$H\gamma$ Central		$H\beta$ Central		$H\delta$ Central		$H\epsilon$ Central	
λ	Setting	λ	Setting	λ	Setting	λ	Setting
406	17.3	440	15.8	396	18.5	384	14.9
410	17.4	444	16.3	400	18.5	388	15.6
414	17.6	448	16.7	404	18.5	392	16.7
418	17.7	452	17.2	408	18.4	396	17.8
422	17.7	456	17.6	412	18.2	400	18.5
426	17.8	460	17.9	416	17.7	...	....
430	17.9	464	18.0	420	17.2	...	....
434	18.0	468	18.1	424	16.6	...	....
438	17.9	472	18.1	428	16.3	...	....
442	17.8	476	18.1	432	15.0	...	....
446	17.7	480	18.1	...	....	...	....
450	17.6	484	18.1	...	....	...	....
454	17.4	488	18.0	...	....	...	....
...	....	492	17.8	...	....	...	....

All this holds for the particular setting of the collimator at 9.8. It is possible to obtain a better focusing of the different rays in a surface for different settings of the collimator scale. For instance, with the collimator setting of 12.0, I obtained the following settings on the scale of camera A:

λ	Setting	λ	Setting
426	14.1	446	14.5
428	14.4	450	14.5
430	14.5	454	14.5
438	14.5	458	13.8
442	14.5	...	....

The edge of the wedge was pointed toward the blue end of the spectrum, and the temperature was +16° C.

For this spectrograph, the curvature of the lines was determined in the following way: Two plates of the iron spectrum were taken with as long a slit as possible, and one spectrum was laid upon the other, under the microscope of the measuring machine, in such a way that the curvature was opposite in the two cases. Identical lines were then brought toward each other until their tips coincided. This gave a figure like a convex lens, the measurement of the thickness of which yielded double the correction for the reduction of the tips of the lines to the center. The length of the line being also known, the parameter of the parabola is computed from these two data. Denoting by x the correction for the curvature, or the abscissa of the parabola, by $2y$ the double ordinate (length of the chord of the "lens"), and by p the parameter, we obtain for the two cameras the following values:

A, $2y$=11.8 mm		B, $2y$=8.1 mm	
λ	$2p$	λ	$2p$
4102	6.16	4102	3.47
4261	6.53	4155	3.47
4427	7.39	4261	3.86
....	....	4315	4.07
....	....	4427	4.19
....	....	4510	4.21

Thence we obtain by means of Hartmann's dispersion formula the following table of corrections, x, together with their values in kilometers:

λ	Camera III A				Camera III B			
	y=1 rev.		y=2 rev.		y=1 rev.		y=2 rev.	
	x	x	x	x	x	x	x	x
418........	0.16 p	0.19 km	0.63 p	0.76 km	0.28 p	0.48 km	1.10 p	1.98 km
422........	.16	.21	.63	.82	.27	.52	1.07	2.06
426........	.15	.21	.61	.85	.26	.52	1.03	2.11
430........	.15	.23	.60	.90	.25	.54	1.00	2.17
434........	.15	.24	.59	.90	.25	.57	0.98	2.21
438........	.14	.24	.57	.91	.24	.57	.97	2.33
442........	.14	.24	.55	.93	.24	.61	.96	2.42
446........					.24	.63	.96	2.51
450........					.24	.65	.95	2.59
454........					.24	.69	.94	2.70

The collimator was very accurately set in line with the optical axis of the thirty-inch telescope. An electric thermostat was also used with exposures on stars, which kept the temperature of the prisms constant for several hours within a range of $0^{\circ}.5$ C.

Nevertheless, in spite of all precautions, the error mentioned at the beginning of this article could not be overcome. The measurement of a series of stellar spectrograms taken under different conditions showed that the difference of the settings on the edges of the spectrograms always kept the same sign, while the absolute magnitude varied. For instance, when the spectrogram was laid on the microscope stage with film up, the settings on the upper edge were always larger than on the lower edge. Only in the position with the camera upward did these differences become smaller and, in a few instances, change their sign. All the other changes were ineffectual on these plates—change of slit-width, of temperature, of width of spectrogram, of hour-angle, and of the diaphragms placed over the collimator lens. (The diaphragms were round and also of the form of segments with the chord parallel to the edge of the prism.) The following table gives these differences arranged for each plate according to the wave-length after a graphical adjustment. If we take the mean for each plate, and then unite these for the mean values for the position of the camera above and camera below, we obtain

For camera below, $+0.019$ rev.
For camera above, -0.001 rev.

It appears that the position of the camera has an effect on the sign of the differences. If we disregard a progressive change in the values depending upon the wave-length, probably due to the diffuseness of the lines at the edge of the field of view, they seem to be otherwise independent of all of the circumstances, such as temperature, camera, width of spectrogram, etc. The measurements of the spectrograms of the Moon show on each plate a progressive change of the differences dependent on the wave-length, but in the mean they are practically zero (-0.0015). It would, therefore, seem that the error under discussion does not occur for spectrograms of disks.

The dependence of the magnitude of the error upon the position of the camera led me to give attention to the optical parts outside of

the spectrograph. It is well known that the thirty-inch telescope has a correcting lens for the violet rays when used for spectrographic purposes. This lens is attached to the tube by a side arm, and is placed at a distance of 174 mm from the focal plane of the thirty-inch objective. This arrangement renders very difficult the centering of this lens; and since its diameter is 60 mm, while the diameter of the cone of rays is 50 mm, it is possible that on account of the flexure of the tube a portion of the rays for certain hour-angles and declinations passes to the side of the lens and unites on the slit of the spectrograph as a visual star. This is seen in the guiding telescope of the spectrograph and held upon the slit. But it may be that this visual image does not coincide with the photographic image. In order to convince myself that this did not happen in our case, the instrument-maker of the Observatory, Mr. Freiberg, made at my request a second guiding telescope for the spectrograph, which was planned to utilize the rays from the first surface of the second prism, hence to see the spectrum of the star. In this way it was possible, without taking the instrument apart, to observe at the same time the direct image of the star and also its spectrum.

The peculiarity at once appeared that when the visually brightest part of the star was set upon the slit, the spectrum between λ 430 and λ 450 was not to be seen; while if the instrument was so held that the spectrum appeared bright, the star itself disappeared from the slit. By means of a micrometer attached to the forty-foot finder of the thirty-inch telescope I then measured the difference in position of the entire instrument for the case of bright star and bright spectrum, and found in the mean a difference of $2''.5$ to $3''$.

I then undertook to make a series of spectrograms by first guiding upon the star and then upon the spectrum. I employed for the purpose *α Boötis*, and obtained in all eight pairs of plates, the measurements of which I give below.

Measurements were made in both directions, and the differences of the setting on the edges of the spectrogram were always formed in the sense upper edge minus lower edge, as seen in the microscope.

TABLE I

DIFFERENCES, IN REVOLUTIONS OF THE SCREW, BETWEEN SETTINGS ON THE UPPER AND LOWER EDGES OF STELLAR SPECTROGRAMS

CAMERA B 1903	*α Persei*					*γ Cephei*	*δ Cephei*		
	Oct. 26	Dec. 12	Dec. 20	Dec. 30	Dec. 30	Sept. 8	Sept. 21	Sept. 18	Sept. 17
Slit-width	18	20	18	15	21	20	20	20	20
Camera setting	18.5	18	18	18	18	18	18	18	18
Temperature	$+1^\circ.5$	-5°	-6°	-6°	-6°	$+12^\circ$	$+13^\circ$	$+12^\circ$	$+11^\circ$
Hour angle	$2^h\ 5^m$E	$2^h\ 20^m$E	$2^h\ 15^m$E	$2^h\ 12^m$E	$1^h\ 6^m$E	$0^h\ 35^m$E	$2^h\ 24^m$E	$2^h\ 24^m$E	$2^h\ 27^m$E
Position of camera	below	below	below	below	below	below	below	above	above
Width of spectrogram	57	84	84	89	89	72	81	81	81

DIFFERENCES: UPPER EDGE—LOWER EDGE

λ 420	....	....	+0.025	+0.030	+0.010	+0.004	....	0.000	....
425	+0.008	+0.032	+ .012	.016	0.017	....	−0.003	.000	−0.002
430	.008	.020	+ .002	.008	.020	.007	+ .003	+ .009	− .002
435	.008	.018	− .001	.007	.018	.011	+ .012	+ .002	− .002
440	.009	.021	− .003	.008	.016	.013	+ .017	− .002	− .003
445	.010	.050	− .002	.015	.010	.020	+ .016	+ .006	− .002
450	.010	....	.000	.035	....	....	+ .012	+ .013	+ .003
Mean	+0.009	+0.030	+0.005	+0.017	+0.015	+0.011	+0.010	+0.004	−0.001

The reading of the scale on the draw-tube was 45 on each day except the first, when it was 40. On the second and third dates a circular diaphragm of 28 mm aperture was used; otherwise none was used.

CAMERA A 1903	*α Boötis*					*β Geminorum*	*α Boötis*		
	Apr. 21	May 8	May 16	May 9	May 17	May 2	1904 May 12	May 17	May 20
Slit-width	16	17	17	16	16	19	13	13	13
Camera setting	13.1	13	13.6	13	13.5	13	13.5	13.2	13.2
Temperature	$+4^\circ$	$+5^\circ.5$	$+8^\circ$	$+2^\circ.8$	$+7^\circ$	$+1^\circ$	$+6^\circ$	$+8^\circ$	....
Hour angle	$0^h\ 45^m$E	$0^h\ 28^m$E	$0^h\ 29^m$E	$0^h\ 15^m$E	$0^h\ 7^m$E	$3^h\ 9^m$W	$1^h\ 2^m$E	$1^h\ 16^m$W	$0^h\ 47^m$W
Position of camera	below	below	above	above	above	below	below	below	below
Width of spectrogram	270	270	270	270	270	130	160	360	160

TABLE I—*Continued*

DIFFERENCES: UPPER EDGE—LOWER EDGE

λ 420	....	....	....	....	−0.010	+0.002	....	....	....
425	+0.020	0.000	−0.010	−0.005	− .006	.012	....	....	....
430	.010	.000	− .013	− .003	− .001	.020	+0.039	+0.032	+0.031
435	.006	.000	− .009	.000	+ .008	.030	.022	.033	.043
440	.010	− .001	.000	.000	+(.017)	.039	.023	.037	.053
445	.010	+ .001	.000	.000	+(.018)	.045	.032	.035	.045
450	.010	+ .004	....	+ .004	+ .019	....	.028	.040	.037
Mean	+0.011	+0.001	−0.006	−0.001	+0.006	+0.025	+0.029	+0.039	+0.042

The reading of the scale on the draw-tube was 40 on each date. On the second, third, fourth, and fifth plates the diaphragm in form of a segment was used.

SPECTROGRAMS OF MOON

1904	Feb. 26	Feb. 28	March 25 (1)	March 25 (2)
λ 418	−0.018 rev.	....	....	....
420	− .005	....	....	....
422	+ .022	....	....	....
424	− .005	+0.004	....	....
425	− .006	....	....	....
427	000	....	.....	....
428	....	+ .019	0.000	−0.007
429	....	....	....	− .016
430	....	....	....	− .010
431	− .007	....	− .003	+ .002
432	....	+ .007	....	....
434	+ .009	....	....	+ .004
435	− .016	+ .009	.000	+ .012
437	....	....	....	+ .023
440	....	....	− .004	+ .024
444	....	....	....	+ .016
445	....	....	− .004	....
447	....	− .008	....	+ .017
449	....	....	....	+ .009
450	....	....	+ .004	....
453	....	− .003	....	+ .007

				λ 428–433	λ 435–453
Mean	−0.003 rev.	+0.005	−0.001	−0.005	+0.015
Orientation in microscope	+0.004	−0.010	+0.003	−0.006	−0.016
Inclination to comparison lines	+0.001 rev.	−0.005	+0.002	−0.011	−0.001

TABLE II

DIFFERENCES IN SETTINGS ON UPPER AND LOWER EDGES OF

Date Guided on	May 12 Star	May 13 (1) Spectrum	May 13 (2) Spectrum	May 17 (1) Spectrum	May 17 (2) Star	May 20 (1) Star	May 20 (2) Spectrum	May 25 (1) Spectrum	May 25 (2) Star
λ									
4294	+0.044	0.000	+0.013	....	+0.030	+0.026	....	....	+0.030
4308	....	....	....	....	....	....	....	....	....
4315	.037	+ .001	+ .001	+0.001	.035	.036	+0.010	+0.008	.014
4325	....	+ .003	....	+ .012	....	....	....	+ .007	....
4326	....	....	....	....	....	.033	....	....	....
4335	....	....	....	....	....	....	....	+ .006	....
4337	0.37	− .005	− .008	− .018	....	....	+ .016	....	....
4340	....	....	....	....	....	....	....	....	....
4345	....	....	− .012	+ .002	....	....	....	....	....
4348	....	....	....	− .011	....	....	....	....	....
4352	....	....	....	....	....	....	− .006	....	....
4353	.016	− .006	+.011	− .002	.040	.049	+ .004	− .002	.019
4356	....	....	....	....	....	.038	....	....	....
4359	....	....	....	....	....	....	+ .008	....	.035
4360	....	....	....	....	....	....	....	....	....
4366	....	....	....	....	.030	....	....	....	....
4371	....	....	....	....	....	....	....	....	.046
4372	....	− .001	....	....	....	....	....	....	....
4376	....	....	+ .005	− .005	....	....	....	+ .007	.032
4379	....	+ .001	− .004	....	....	....	....	....	....
4401	....	+ .017	....	....	....	....	....	....	....
4405	.023	+ .007	− .006	....	.037	....	....	....	....
4406	....	....	....	....	....	....	....	....	....
4407	....	....	− .004	+ .005	....	....	....	+ .006	....
4408	....	....	+ .005	....	....	....	....	+ .002	....
4409	....	+ .010	....	....	.040	.033	+ .003	....	.028
4415	....	+ .003	....	....	....	....	....	....	....
4427	.020	+ .003	− .002	− .006	.046	.042	+ .006	+ .005	.034
4442	....	....	....	....	....	....	....	....	....
4443	....	+ .001	....	− .003	....	....	....	....	....
4448	.033	....	....	....	....	....	....	− .006	....
4451	....	....	....	....	....	....	....	....	....
4459	.030	+ .001	− .008	....	....	.052	+ .020	+ .005	.030
4460	....	....	....	....	....	....	....	....	....
4461	....	....	....	....	....	.037	....	....	....
4467	....	....	....	....	.036	....	....	....	.025
4476	....	+ .001	....	....	.054	....	....	....	....
4482	....	....	− .002	....	....	....	+ .015	....	.034
4485	....	....	....	....	....	....	....	....	....
4495	....	+ .004	....	....	....	.021	....	....	....
4496	....	....	....	....	....	....	....	....	....
4527	....	....	....	....	....	.052	....	....	....
4529	.028	− .002	− .004	....	.039	....	+ .031	+ .012	.046
4531	....	....	....	....	....	....	....	....	....
4536	....	+ .003	....	....	.043	.045	+ .022	+ .009	.043
4550	....	....	− .003	....	....	.038	....	+ .009	.047
4566	....	....	....	....	....	....	....	....	....
4600	....	....	− .001	....	....	....	....	....	....
4603	....	....	....	....	.051	....	....	....	....
Means	+0.030	+0.002	−0.001	−0.002	+0.040	+0.040	+0.012	+0.005	+0.033

TABLE II

SPECTROGRAMS OF α *Boötis*, 1904, EXPRESSED IN REVOLUTIONS OF THE SCREW

Date Guided on	May 25 (3) Spectrum	May 26 (1) Star	May 26 (2) Spectrum	May 29 (1) Spectrum	May 29 (2) Star	May 30 (1) Star	May 30 (2) Spectrum	May 31 (1) Star	May 31 (2) Spectrum
λ									
4294	+0.015	+0.030	+0.030	......	+0.030	+0.055	......	......	......
4308	......	......	......	......	......	......	......	......	+0.011
4315	−0.003	.006	.018	+0.006	.024	.022	+0.014	+0.026	(+ .022)
4325	− .013	......	.013	......	......	......	.004	......	......
4326	......	......	......	.006	......	.032	......	......	+ .004
4335	......	......	......	......	......	......	.001	......	......
4337	......	......	.029	.012	......	......	......	......	......
4340	......	......	.001	......	......	.043	......	......	......
4345	+ .005	......	......	......	......	......	......	.041	......
4348	......	......	......	......	......	......	......	......	......
4352	......	......	......	......	......	.033	......	......	......
4353	+ .002	.023	.001	.014	.029	......	.013	.020	+ .002
4356	......	......	......	......	......	......	......	......	......
4359	......	......	......	......	......	......	......	......	......
4360	+ .009	......	......	......	.030	......	......	......	......
4366	......	......	......	......	......	......	......	......	......
4371	......	......	......	......	.033	......	......	......	......
4372	......	......	......	......	......	......	......	......	......
4376	......	......	......	.008	......	.039	.010	......	......
4379	......	......	......	......	......	......	......	......	− .008
4401	......	......	......	......	......	......	......	......	......
4405	......	......	......	......	......	......	......	......	......
4406	......	......	......	......	......	......	......	......	+ .005
4407	......	......	......	......	......	......	......	......	......
4408	......	.040	......	......	......	......	......	......	......
4409	+ .017	......	......	......	.029	.028	.005	.020	......
4415	......	......	......	.008	......	......	.004	.034	......
4427	+ .012	.020	.017	.016	.028	.028	.006	.026	+ .007
4442	......	......	......	.002	......	......	......	......	......
4443	......	......	......	......	......	......	......	......	......
4448	......	......	.016	......	......	......	......	......	......
4451	......	......	......	......	......	......	......	.036	......
4459	+ .003	.021	.021	......	.044	.030	......	.026	+ .010
4460	......	......	......	......	......	......	.005	......	......
4461	......	......	......	......	......	......	......	......	......
4467	......	......	......	.005	......	......	......	......	......
4476	......	.030	......	.015	......	......	......	.020	......
4482	+ .005	......	.013	......	.039	......	.008	......	......
4485	......	......	......	......	......	......	......	......	.000
4495	......	......	......	......	......	......	......	......	......
4496	+ .007	......	.011	......	......	......	......	.023	......
4527	......	......	......	......	......	......	......	......	......
4529	+ .016	.032	.009	.011	.032	.035	.008	.024	+ .013
4531	+ .013	......	......	......	......	......	......	......	......
4536	......	.020	......	.006	.014	.041	......	......	+ .001
4550	......	......	+ .005	......	......	......	......	......	......
4566	+ .006	......	− .004	......	......	......	......	......	......
4600	......	......	......	......	......	......	......	......	......
4603	......	......	......	......	......	......	......	......	......
Means	+0.007	+0.025	+0.013	+0.009	+0.030	+0.035	+0.006	+0.027	+0.006

If we form the means of these differences for each plate, and combine them into two groups according to whether the guiding was done by the star image or by the spectrum, we obtain the following results:

Guiding on Star				Guiding on Spectrum			
	rev.		rev.		rev.		rev.
May 12	+0.030	May 26.1	+0.025	May 13.1	+0.002	May 25.3	+0.007
17.2	040	29.2	.030	13.2	− .001	26.2	.006
20.1	.040	30.1	.035	17.1	− .002	29.1	.009
25.2	.033	31.1	.027	20.2	+ .012	30.2	.006
				25.1	+ .005	31.2	.006

If we now form the mean from each of the series, we obtain for the case of guiding by the star the difference +0.033 rev. ±0.002 (mean error always given here); and for the case of guiding on the spectrum +0.005 ±0.001. Expressed in kilometers, these differences amount to

$$+5.70\,\text{km} \pm 0.34 \; (\lambda=4419) \;.$$
$$+0.85\,\text{km} \pm 0.27 \; (\lambda=4409) \;.$$

We see from this how easy it is to make an error of 1 and more kilometers if, during the measurement, the settings are not made rigorously in the center of the spectrum, for the case that the spectrogram was obtained by holding the star on the slit during the guiding. The residual value of +0.85 km probably depends on the fact that my eye is blind to the violet end of the spectrum, and I can see the continuous spectrum only to $H\gamma$, so that I can give attention only to the region from $H\gamma$ to $H\beta$. The quality of the images may also have had some effect here.

Inasmuch as *a Boötis* has been repeatedly observed at several observatories, it was interesting to compare the results of my present determinations of radial velocity with the mean value of other determinations. For this purpose I computed the wave-lengths of the edges of the spectrogram and reduced them to the center by means of the differences obtained above. Since the wedge under the plate was in three instances placed with its edge toward the blue end of the spectrum, I computed a new formula. The coefficients of the

formula for $a=\frac{1}{2}$ were computed from the mean settings n on all spectrograms of the following iron lines, after the plates had all been reduced to the same dispersion.

λ 4293.410 - - - - -	$n=$ 2.579 rev.
4404.928 - - - - -	48.565
4528.798 - - - - -	94.306

The formula for determining the wave-length is

$$\lambda=3371.316+\left(\frac{[3.9269484]}{879.887-n}\right)^2 \qquad (1)$$

For the determination of n, it is

$$879.887-n=\frac{[3.9269484]}{(\lambda-3371.316)^{\frac{1}{2}}} \qquad (2)$$

In order to judge how far this formula satisfies the measurements of other lines, I computed by formula (1) the wave-length from the mean n, and compared it with the values taken from Rowland's table.

λ	C.-O.	λ	C.-O.	λ	C.-O.	λ	C.-O.
	t.-m.		t.-m.		t.-m.		t.-m.
4294.301	+0.007	4352.908	−0.007	4427.482	+0.003	(4476.185)	....
4299.410	0	4376.105	0	4442.510	− 6	(4482.338)	....
4308.081	+ 7	4383.720	+ 5	4447.892	− 11	4494.738	+0.003
4315.262	− 4	4404.928	0	4459.301	+ 5	4528.798	0
4325.939	− 2	4415.293	+ 7	4466.727	− 2	(4603.126)	....
4337.216	− 8						

In order to compute the wave-lengths of the star lines, Rowland's values were employed, and the corresponding n was calculated by formula (2). The values of n corresponding to the *Fe* lines on each plate were reduced to these values and were graphically adjusted, and then similarly the values of n for the star lines. Finally, the wave-lengths were computed according to formula (1) and compared with Rowland's. The differences of wave-lengths were expressed in kilometers by the formula

$$S=\frac{300\,000}{\lambda}\cdot\frac{(\lambda-3371.3)^{1.5}}{[3.6253]}.$$

In the following tables, III, *a*, *b*, all the data for the determination of velocity are given. All the columns may be readily understood. V_a, V_d, and C denote the reduction to the Sun, the correction for the daily motion, and the correction for the curvature of the lines.

TABLE III*a*

α Boötis 1904

Poulkova M. T.	Exposure	Hour Angle	Slit-Width	Comparison Spectrum	Guided on	Width of Spectrogram	Where Measured	Temp.
May 12.403	31^m	$1^h\ 2^m$ E	13	*Fe* 30^smd	Star	0.160 R	Lower edge	+6°.0+5°.7 C.
13.388	29	1 38 E	13	30	Spectrum	.160	Center	+7°.0
13.414	37	1 2 E	13	30	Spectrum	.634	Center	+7.0
17.422	46	0 47 E	13	33	Spectrum	.360	Center	+8.2
17.498	37	1 16 W	12	30	Star	.360	Lower edge	+8.0
20.413	38	0 47 E	13	30	Star	.160	" "	+7.7
20.438	34	0 2 W	12.5	30	Spectrum	.160	" "	+7.5
25.409	30	0 21 E	12.5	33	Spectrum	.160	Center	+6.0
25.461	47	0 54 W	12.5	30	Star	.160	Lower edge	
25.490	32	1 36 W	12.5	30	Spectrum	.360	Center	+5.8
26.478	36	1 23 W	12	30	Star	.160	Lower edge	+9.0
26.504	31	2 0 W	12	30	Spectrum	.160	" "	+8.7
29.422	37	0 14 W	12	33	Spectrum	.160	" "	+7.5
29.452	44	0 57 W	12	35	Star	.160	" "	+7.5
30.423	27	0 21 W	12	34	Star	.160	" "	+6.0
30.450	42	0 57 W	12	34	Spectrum	.160	" "	+5.8
31.421	37	0 21 W	12	33	Star	.160	" "	+7.2
31.450	40	1 2 W	12	33	Spectrum	.160	" "	+7.0

The light from the *Fe* spark always passes through a ground glass disk.
The camera setting was 13.2 for each of the above plates.

TABLE III*b*

n	λ	Δλ	Vel.
	May 12		
0.151R	4294.296	+0.092t.-m.	+6.42km
9.925	4315.151	.056	3.89
19.928	4337.236	.020	1.38
26.863	4353.006	.075	5.16
48.590	4404.992	.065	4.43
57.501	4427.514	.094	6.37
63.297	4442.560	.050	3.37
69.647	4459.418	.061	4.10
94.331	4528.873	.075	4.97
96.749	4536.032	.040	2.65
		Mean	+ 4.27km
		Va	−11.86
		Vd	+ 0.06
		C.........	− 0.18
		ρ[1]	− 7.71
	May 13 (1)		
0.217R	4294.434	+0.133t.-m.	+ 9.27km
9.987	4315.286	.077	5.35
14.932	4326.108	.149	10.33
19.987	4337.369	.153	10.58
26.904	4353.101	.057	3.93
34.788	4371.502	.060	4.12
38.142	4379.490	.094	6.43
46.900	4400.802	.064	4.36
48.595	4405.004	.077	5.24
50.071	4408.685	.103	7.00
52.746	4415.407	.114	7.74
57.511	4427.540	.058	3.23
63.321	4442.624	.114	7.69
69.649	4459.423	.122	8.20
75.875	4476.340	.085	5.69
82.533	4494.867	.129	8.61
94.368	4528.982	.053	3.51
96.794	4536.167	.073	4.82
102.324	4552.794	.069	4.54
106.602	4565.202	.060	3.94
		Mean.....	+ 6.26km
		Va	−12.24
		Vd........	+ .08
		C.........	− .18
		ρ..........	− 6.08
	May 13 (2)		
0.230R	4294.461	+0.160t.-m.	+11.18k.m.
9.993	4315.289	.151	10.49
20.000	4337.398	.182	12.58
23.266	4344.779	.109	7.52
26.919	4353.134	.090	6.20
36.800	4376.283	.176	12.06
38.171	4379.560	.164	11.03
48.611	4405.044	.117	7.97
49.385	4406.972	.162	11.03
49.805	4408.020	.149	10.14
57.530	4427.588	.106	7.18
60.672	4459.485	.128	8.61
78.130	4482.565	.127	8.50
94.887	4520.047	.118	7.81
118.474	4603.444	.163	10.62
	May 13 (2)—*Continued*		
		Mean.....	+ 9.54km
		Va........	−12.25
		Vd........	+ .06
		C.........	− 2.38
		ρ..........	−5.03
	May 17 (1)		
9.652R	4314.559	+0.129t.-m.	+ 8.96km
10.000	4315.314	.105	7.30
19.995	4337.387	.171	11.82
23.268	4344.783	.113	7.80
24.768	4348.201	.071	4.89
26.917	4353.130	.086	5.93
36.804	4376.293	.186	12.75
49.380	4406.959	.149	10.14
57.525	4427.573	.091	6.17
63.346	4442.689	.179	12.08
		Mean.....	+ 9.37km
		Va........	−13.72
		Vd........	+ .05
		C.........	− .76
		ρ..........	− 5.06
	May 17 (2)		
0.158R	4294.301	+0.106t.-m.	+ 7.40km
9.939	4315.160	.022	1.53
26.867	4353.015	.107	7.37
34.768	4371.456	.088	6.04
48.575	4404.955	.028	1.91
50.060	4408.658	.076	5.17
57.498	4427.506	.086	5.83
72.409	4466.874	.147	10.95
75.844	4476.255	.070	4.69
94.344	4528.911	.113	7.48
96.756	4536.053	.174	11.50
111.668	4581.710	.135	8.84
		Mean.....	+ 6.56km
		Va........	−13.75
		Vd........	− .07
		C.........	− .76
		ρ..........	− 8.02
	May 20 (1)		
0.155	4294.304	+0.100t.-m.	+ 6.98km
9.944	4315.193	.098	6.81
14.891	4326.020	.081	5.62
26.852	4352.980	.072	4.96
34.761	4371.440	.072	4.94
50.052	4408.637	.055	3.74
57.501	4427.514	.094	6.37
69.639	4459.397	.096	6.46
73.433	4469.659	.114	7.65
82.499	4494.775	.119	7.94
94.325	4528.855	.057	3.77
96.762	4536.071	.049	3.24
101.380	4549.931	.124	8.11

[1] The symbol $\bar{\rho}$ is used in these tables for the radial velocity of the star referred to the Sun.

TABLE III*b*—*Continued*

n	λ	Δλ	Vel.
	May 20 (1)—*Continued*		
		Mean.....	+ 5.89km
		Va........	−14.76
		Vd........	− .05
		C.........	− .18
		ρ	− 9.10
	May 20 (2)		
9.996R	4315.306	+0.168t.-m.	+11.68km
14.945	4326.139	.150	10.40
19.008	4335.173	.139	9.61
26.513	4352.201	.118	8.13
26.928	4353.155	.111	7.65
29.854	4359.927	.143	9.83
50.092	4408.737	.155	10.54*
57.537	4427.607	.125	8.46
69.664	4459.463	.162	10.89
78.122	4482.543	.105	7.03
94.377	4529.009	.080	5.30
96.802	4536.189	.095	6.28
		Mean.....	+ 8.82km
		Va........	−14.76
		Vd........	.00
		C.........	− .18
		ρ	− 6.12
	May 25 (1)		
10.006R	4315.327	+0.118t.-m.	+ 8.19km
14.621	4325.424	.118	8.17
19.019	4335.220	.136	12.86
26.936	4353.174	.130	8.96
36.802	4376.388	.181	12.41
49.383	4406.966	.156	10.61
49.809	4408.040	.169	11.50
57.538	4427.609	.189	12.80
65.380	4448.047	.155	10.45
69.678	4459.501	.144	9.64
94.387	4529.038	.109	7.21
96.807	4536.205	.157	10.38
		Mean.....	+10.27
		Va........	−16.41
		Vd........	+ .02
		C.........	− .18
		ρ	− 6.30
	May 25 (2)		
0.186R	4294.369	+0.096t.-m.	+ 6.70km
9.964	4315.236	.098	6.81
26.892	4353.073	.142	9.78
29.825	4359.859	.075	5.13
34.756	4371.428	.060	4.12
36.740	4376.141	.034	2.33
50.058	4408.662	.080	5.44
57.509	4427.534	.114	7.72
69.638	4459.396	.095	6.39
72.417	4466.896	.133	8.93
78.088	4482.438	.100	6.69
94.335	4528.974	.163	10.79
	May 25 (2)—*Continued*		
96.767	4536.086	.177	11.70
101.386	4549.949	.141	9.29
		Mean.....	+ 7.27km
		Va........	−16.45
		Vd........	− .06
		C.........	− .18
		ρ	− 9.42
	May 25 (3)		
0.235	4294.472	+0.171t.-m.	+11.94km
10.012	4315.340	.131	9.10
14.639	4325.464	.163	11.30
23.279	4344.808	.138	9.52
26.932	4353.164	.233	16.05
29.879	4359.985	.176	12.11
50.103	4408.765	.143	9.72
57.540	4427.614	.194	13.14
69.693	4459.538	.181	12.17
78.153	4482.628	.190	12.72
83.124	4496.538	.220	14.67
94.390	4529.047	.236	15.63
96.823	4536.253	.205	13.74
106.636	4566.008	.166	10.90
		Mean.....	+12.34km
		Va........	−16.46
		Vd........	− .08
		C.........	− .76
		ρ	− 4.96
	May 26 (1)		
0.184	4294.365	+0.161t.-m.	+12.24km
9.978	4315.266	.128	8.89
26.896	4353.082	.174	11.99
49.778	4407.953	.143	9.73
57.513	4427.545	.125	8.47
69.649	4459.423	.122	8.20
75.867	4476.312	.127	8.51
94.342	4528.906	.108	7.15
96.778	4536.119	.097	6.41
		Mean.....	+ 9.07km
		Va........	−16.78
		Vd........	− .07
		C.........	− .18
		ρ	− 7.96
	May 26 (2)		
0.205	4294.409	+0.136t.-m.	+ 9.50km
9.979	4315.266	.128	8.89
14.602	4325.382	.199	13.80
19.986	4337.367	.151	10.42
21.103	4338.882	.151	10.43
26.920	4353.137	.093	6.41
57.515	4427.550	.130	8.80
65.389	4448.070	.178	12.00
69.655	4459.439	.138	9.28
78.121	4482.540	.165	11.04
83.108	4496.493	.175	11.67

TABLE III*b*—*Continued*

n	λ	Δλ	Vel.
May 26 (2)—*Continued*			
94.372	4528.995	.197	13.04
101.431	4550.085	.185	12.20
113.213	4586.593	.185	12.10
		Mean.....	+10.68km
		Va........	−16.78
		Vd........	− .10
		C.........	− .18
		ρ..........	− 6.38
May 29 (1)			
10.005R	4315.325	+0.187t.-m.	+12.99km
14.953	4326.156	.197	13.66
20.012	4337.425	.209	14.45
26.931	4353.162	.118	8.13
36.810	4376.307	.200	13.71
52.779	4415.489	.196	13.31
57.539	4427.612	.130	8.80
63.363	4442.734	.208	14.04
72.463	4467.020	.134	8.99
75.891	4476.384	.199	13.34
94.381	4529.021	.223	14.76
96.814	4536.226	.132	8.73
		Mean.....	+12.08km
		Va........	−17.68
		Vd........	− .01
		C.........	− .18
		ρ..........	− 5.79
May 29 (2)			
0.169R	4294.333	+0.129t.-m.	+ 9.01km
9.951	4315.208	.113	7.85
26.888	4353.064	.133	9.16
29.837	4359.887	.103	8.08
34.781	4371.487	.119	8.16
50.069	4408.680	.098	6.66
57.518	4427.557	.137	9.28
69.653	4459.434	.133	8.94
78.092	4482.459	.121	8.10
94.344	4528.911	.113	7.48
96.793	4536.160	.112	7.41
		Mean.....	+ 8.19km
		Va........	−17.69
		Vd........	− .06
		C.........	− .18
		ρ..........	− 9.74
May 30 (1)			
0.176R	4294.348	+0.144t.-m.	+10.05km
9.960	4315.227	0.089	6.19
14.998	4326.256	.137	9.50
21.067	4339.800	.183	12.64
26.470	4352.102	.172	11.85
36.742	4376.145	(.038)	(2.60)
50.079	4408.705	.123	8.36
57.512	4427.549	.122	8.27
69.662	4459.458	.157	10.56
94.346	4528.917	.119	7.88
96.773	4536.104	.195	12.89
May 30 (1)—*Continued*			
		Mean.....	+ 9.89km
		Va........	−17.99
		Vd........	− .02
		C.........	− .18
		ρ..........	− 8.37
May 30 (2)			
10.005R	4315.325	+0.116t.-m.	+ 8.06km
14.635	4325.446	.141	9.71
19.030	4335.007	.174	12.03
26.935	4353.172	.128	8.82
36.818	4376.326	.219	15.01
50.108	4408.777	.155	10.54
52.785	4415.504	.211	14.87
57.564	4427.676	.194	13.14
69.708	4459.591	.224	15.03
78.158	4482.642	.204	13.65
94.403	4529.086	.157	10.40
		Mean.....	+12.91km
		Va........	−17.99
		Vd........	− .06
		C.........	− .18
		ρ..........	− 5.32
May 31 (1)			
9.604R	4314.455	+0.174t.-m.	+12.09km
21.465	4340.699	(.065)	(+ 4.49)
26.892	4353.073	.142	9.78
50.069	4408.680	.098	6.67
52.742	4415.395	.102	6.93
57.508	4427.532	.112	7.59
66.364	4450.655	.173	11.64
69.653	4459.434	.134	9.01
75.863	4476.307	.122	8.18
83.075	4496.400	.179	11.94
96.764	4536.007	.168	11.11
		Mean.....	+ 9.23km
		Va........	−18.27
		Vd........	− .01
		C.........	− .18
		ρ..........	− 9.23
May 31 (2)			
6.715R	4308.225	+0.202t.-m.	+14.06km
9.975	4315.260	.166	11.53
14.938	4326.123	.184	12.76
26.932	4353.164	.233	16.05
38.179	4379.579	.183	12.53
49.110	4406.287	.180	12.26
50.110	4408.782	.160	10.88
57.540	4427.614	.194	14.74
69.674	4459.490	.189	12.71
94.377	4529.009	.211	13.96
96.804	4536.196	.204	13.49
		Mean.....	+13.27km
		Va........	−18.28
		Vd........	− .06
		C.........	− .18
		ρ..........	− 5.25

Values enclosed in parentheses were not used.

TABLE IV

SUMMARY

	Lower Edge	Red. to Center		Lower Edge	Red. to Center	
May 12	−7.39 km	+2.85 km	May 13 (1)	−6.08 km	0.00 km	−6.08 km
17 (2)	8.02	2.85	13 (2)	5.03	0.00	5.03
20 (1)	9.10	2.85	17 (1)	5.06	0.00	5.06
25 (2)	9.42	2.85	20 (2)	5.95	+1.02	4.93
26 (1)	7.96	2.85	25 (1)	6.30	0.72	5.58
29 (2)	9.74	2.85	25 (3)	4.96	0.72	4.24
30 (1)	8.37	2.85	26 (2)	6.38	1.11	5.27
31 (1)	9.23	2.85	29 (1)	5.79	0.77	5.02
			30 (2)	5.32	0.52	4.80
			31 (2)	5.25	0.53	4.72
Mean	−8.65				Mean	−5.07 km
	+2.85					
	−5.80					

Final mean, radial velocity =−5.44 km at epoch 1904.39.

Table IV gives a summary of the velocities thus obtained. We see that for the plates obtained when the visual star was held on the slit the velocity differs 0.5 km from that given when the spectrum was kept at its brightest by guiding. If we collect the observations of this star, we obtain the following values:

Potsdam, 1889, - - - - -	−7.7 km
Keeler, - - - - - -	6.9
Bélopolsky, 1893, - - - - -	5.7
Frost and Adams, 1902, - - -	4.3
Newall, 1903, - - - - -	5.8
Frost and Adams, 1903, - - -	4.8
Bélopolsky, 1903, - - - - -	6.1
Bélopolsky, 1904, - - - -	5.5
Mean, - - - - - -	−5.85

But if we combine only the results since 1902, we obtain −5.3 km. We might, therefore, infer that guiding on the brightest part of the spectrum yielded a result almost free from error, but by guiding with the visual star upon the slit we obtain a spectrogram which, on account of the diffuseness of the lines and their inclination to the artificial lines, give worse results. In this case it is especially important in making the settings under the microscope that the center of the spectrum is measured.

It thus appears that for the Poulkova instrument the false inclination of the stellar lines with respect to the comparison lines is due to

the fact that the photographic rays fall upon the collimator lens obliquely, and thus have a different path through the prisms from that of the rays from the iron arc. Hence a photographic plate placed just back of the collimator lens is illuminated over only half of the aperture.

I cannot yet decide to what extent this error enters in the case of spectrograms of planets. It is true that the lines in the spectrum of the Moon show no inclination with respect to the comparison lines. But the fact that in the case of the stellar spectra the inclination changes its sign when the spectrograph is rotated 180° about the optical axis of the thirty-inch refractor, would indicate that in the case of the planets the rotation of the spectrograph does not furnish a criterion of the true inclination. *Jupiter* is also not suitable for serving as a check, as the great variations of the velocity by zones requires that the setting should be made on precisely the same points of the disk, which is exceedingly difficult if the magnification of the guiding telescope is insufficient. In our case, the further circumstance enters that the visual disk does not coincide with the photographic.

TABLE V

ROWLAND'S WAVE-LENGTHS OF LINES USED

Rowland	Int.	Blend	Rowland	Int.	Blend
λ		λ	λ		λ
4294.204	2	4294.273	4459.199	2	4459.260
4.310	5		9.301	3	
					4459.357
4307.907	3	4308.023	4459.525	1	
8.081	6				
			4466.727	5	
4314.248	3	4314.281			
4.381	1		4476.185	4	4476.214
4.479	1	4314.430	6.253	3	
4314.964	1	4315.095	4482.338	5	4482.376
5.138	3		2.438	3	
5.262	4	4315.209			
			4494.738	6	
4325.152	4	4325.183			
5.306	1		4496.125	1	
			6.318	1	
4325.939	8	4325.959			
6.119	1		4528.798	8	4528.811
			8.929	0	

TABLE V—*Continued*

Rowland	Int.	Blend
4334.965	0	4335.034
5.102	0	
4337.216	5	
4339.617	4	4339.731
9.882	3	
4340.634	20	
4344.670	4	
4348.130	1	4348.045
8.003	2	
4351.930	5	4352.007
2.083	5	
4352.908	4	4352.931
3.044	0	
4359.784	3	4359.809
9.907	0	
4371.221	1	4371.368
1.442	2	
4376.107	2	
4379.396	4	
4400.738	1	4400.601
0.551	3	
4404.927	10	
4406.810	2	
4407.810	2	4407.851
7.871	4	
4408.583	3	4408.622
8.683	2	
4415.293	8	
4427.266	2	4427.420
7.482	5	
4442.510	6	4442.526
2.621	1	
4447.892	6	
4450.482	1	4450.597
0.654	2	

Rowland	Int.	Blend
4535.879	1	4535.992
5.909	0	
6.094	2	4536.022
		4536.048
4549.808	6	4549.814
9.990	0	
		4559.814
4559.802	6	
9.900	0	4565.854
4565.842	2	
5.905	00	
4581.575	4	4581.635
1.694	4	
4586.408	1	
6.552	1	
4603.126	6	

Table V gives the wave-lengths from Rowland's table which I have used. The column "Blend" contains the wave-lengths of the lines which lie so close together that they do not appear separated on the stellar spectrogram. In such cases the weight was assigned proportionately to the intensity.

POULKOVA, November 1904.

ON THE SPECTRUM OF MAGNESIUM

By JAMES BARNES

The magnesium spectrum is of much interest on account of its presence in the spectrum of many[1] stars, and also on account of its application in the determination of stellar[2] temperatures.

The line λ 4481 appears very strong in the spectra of numerous stars belonging to Vogel's first type, while λ 4352 is very faint or not present. From these facts Scheiner drew the conclusion that on the stars of the first type the temperature of the absorbing layer was approximately that of the electric spark, while on the stars in whose spectrum the line λ 4352 more strongly occurs the temperature was about that of the electric arc. Just what Scheiner meant by the temperature of the spark is not clear, for the words "temperature of the spark" have in themselves no meaning according to our present ideas based on the kinetic theory of gases. Recently Hartmann[3] has shown that the presence or absence of these lines is no indication of high or low temperatures; that is, the lines λ 4481 and λ 4352 are not due to temperature, but rather to electrical causes.

The so-called spark lines are those which appear in the electric spark produced by a high-tension discharge and are rarely present in the arc running under the ordinary voltage and current. The arc lines are those that appear in the arc and are of weak intensity or not visible in the spark discharge.

It was the object of this work to repeat the observations of Hartmann, and also to study the other conditions which might be found to enhance or diminish the intensity of these lines.

I need only briefly refer to the work of Liveing and Dewar,[4] who first observed the presence of spark lines in the arc produced between thick electrodes of magnesium, when surrounded by air, carbonic acid, ammonia, etc. From their results they threw doubt on the then accepted opinion that the temperature of the spark discharge

[1] H. C. Vogel, *Astronomische Nachrichten*, **161**, 365, 1903.

[2] H. Kayser, *ibid.*, **162**, 277, 1903.

[3] *Astrophysical Journal*, **17**, 270, 1903. [4] *Proc. R. S.* **44**, 241, 1888.

was much higher than that of the arc. They believed that the production of the spark lines was conditioned by the energy of the electric discharge, and not by any change in the temperature.

This important result led the way for further investigation. Crew[1] found the spark line λ 4481 to be one of the strongest lines in the spectrum obtained with his "rotating" arc. This line was intensified when the arc was surrounded by hydrogen, while the lines belonging to the Kayser and Runge series were unaffected. Porter[2] with the same arc in nitrogen found this line reduced to about one-fifth of its intensity in air. Schenck[3] observed that the intensity of the line λ 4481 decreases in the spark spectrum if the electrodes are heated to the point of melting. Hartmann[4] and Eberhard observed that the spark line appeared in the spectrum of the arc under water, the effect being analogous to that produced by hydrogen on the arc. Recently Hartmann[5] has been able in the case of magnesium and bismuth to transform the arc spectrum into the spark spectrum without changing in any way the surrounding dielectric, by merely diminishing the strength of the current. From the results of this very careful experiment he has conclusively shown, as was believed by Liveing and Dewar, that the presence of the line λ 4481 is no proof of high temperatures, but is rather due to electro-luminescence.

Hartmann concludes, however, that λ 4481 results from the vibrations of particles highly charged with electricity, and that the charge carried by a particle is a function of the resistance of the arc. The greater the conductivity, the less the charge, and hence a smaller intensity of this line. This conclusion is partly based on the observation that the intensity of λ 4481 decreases if the dielectric surrounding a spark is reduced by exhaustion. In the arc he considers that the same effect happens. This explanation was not satisfactory to me, and was overthrown when it was found that experiments gave just the opposite result, namely, that the line λ 4481 was enhanced when the density of the dielectric surrounding the arc was diminished.

The work was carried on with the following apparatus: A Rowland concave grating of about thirteen feet radius was used, and photo-

[1] *Phil. Mag.*, (5) **38**, 379, 1894.

[2] *Astrophysical Journal*, **15**, 274, 1902.

[3] *Ibid.*, **14**, 116, 1901.

[4] *Ibid.*, **17**, 229, 1903.

[5] *Ibid.*, **17**, 270, 1903.

graphs were taken in the first spectrum, since in this order it was the most brilliant. Later in the work a smaller grating with radius of 60 cm was found sufficient for the problems in view.

Solid magnesium rods of about 1 cm diameter were employed as electrodes. These, suitably mounted, were inclosed in a glass vessel of 800 cu.cm capacity and having a long neck, over the end of which was sealed a piece of plate glass. In the two openings in the sides of the vessel were placed rubber stoppers conveying the supports for the electrodes and the electrical connections. A glass tube connects with the hydrogen generator and the Geryk exhaust pump. Soon after the arc is started, the bulb of the vessel is covered with a deposit of magnesium thrown off from the arc; this, however, does not penetrate into the neck, so that the radiation passes through to the slit of the grating without loss. The rubber stoppers allowed the electrodes to be slightly moved without affecting the pressure in the vessel. In this way the electrodes could be brought together to strike the arc. The hydrogen was obtained by the ordinary method of the action of hydrochloric acid upon granulated zinc. It was passed through sulphuric acid before entering the vessel containing the arc.

The current was obtained from a 110-volt circuit, and its strength was varied by resistances consisting of incandescent lamps. When the spark was employed it was produced by an ordinary induction coil.

With the magnesium arc burning in air the electrodes soon became coated with the oxide, and this had to be removed when small current-strengths were employed before an arc could be again started. As the arc had to be made a great number of times during one exposure, plates were taken only when the air surrounding the arc was at atmospheric pressure, when the magnesium oxide could be easily removed; and also at very low pressures, when the little oxide formed did not interfere with the striking of the arc whenever required. At other pressures below the atmospheric it was impossible to clean the electrodes without opening the vessel and thereby changing the pressure. As hydrogen does not unite with magnesium, observations could be obtained without difficulty at any pressure.

RESULTS

After taking a systematic series of photographs of the spectrum of the arc under different current-strengths and pressures of the surrounding gas, it was found that the intensities of the lines in the first subordinate series λλ 3838.4, 3832.4, and 3829.5, and in the second subordinate series λλ 5183.8, 5172.8, and 5167.5, were practically unaffected. These lines in the spark are also unaffected by any change in pressure of the surrounding dielectric. Thus the intensity of the line λ 5183.8 has been taken as the standard, which is called 10; a line barely visible on the negatives is given the intensity 1. The following tables contain the results obtained; the pressures are given in millimeters of mercury and the current-strengths in amperes.

ARC IN AIR

Wave-Length	Pressure	Intensity when Current-Strength is				
		7.5	3.5	2.0	1.0	0.5 amperes
4703.2 (arc line)....	760mm	10	10		10	8
	1		8	8	8	7
4571.3 (arc)........	760	6	6		4	4
	1		1	0	0	0
4481 (spark)........	760	0	1		10	15
	1		20	20	20	20
4352.1 (arc)........	760	10	10		10	8
	1		3	2	1	1
4167.8 (arc)........	760	7	7		7	5
	1		1	1	1	1
4058.4 (arc)........	760	5	5		5	4
	1		1	1	0	0

ARC IN HYDROGEN

Wave-Length	Pressure	Intensity when Current-Strength is	
		3.5	0.5 amperes
4703.2...........	760mm	6	2
	380	6	1
4481.............	760	5	15
	380	10	15
4352.1...........	760	4	0
	380	3	0

The other arc lines are omitted from the hydrogen part of the

table, as they do not appear on the plates at any pressure or current-strength.

These tables show that all the arc lines are weakened when the strength of the current is diminished, both at atmospheric and lower pressures when the dielectric is air or hydrogen. In air the change in intensity is slight. Also, with the same current and pressure hydrogen diminishes the intensity of the arc lines, while the spark line is enhanced, which is in accordance with the results of Crew. It is also seen how the remarkable spark line λ 4481 is intensified in air as the current is decreased, thus confirming the observations of Hartmann. In both air and hydrogen, using the arc, a decrease of the pressure always weakens the arc lines and intensifies the spark lines. It is important to note that the intensity of the line λ 4481 in a vacuum of about 1 mm pressure does not change its intensity with the variation of current throughout the range employed. It is also worth remarking that the plate taken of the spectrum of the spark obtained with an induction coil having a Leyden jar in parallel with the secondary was so similar to the one taken of the spectrum of the arc in a vacuum that almost no difference was perceptible. The distance between the electrodes in all the observations was not more, generally less, than a few millimeters. The voltage across the electrodes was about forty volts.

With regard to the spectrum of zinc, cadmium, and bismuth very few conclusive results were obtained. If a transformation of the arc spectrum into the spark spectrum happened, it was much less striking than in the case of magnesium, where the steps were easily obtained. The observation of Hartmann that the zinc spark lines λ 4912 and λ 4925 appeared in the arc spectrum on reducing the current to 0.5 ampere was corroborated. In a vacuum it was found that these spark lines made their appearance in the arc when not a trace of them could be found in the arc surrounded by air at atmospheric pressure, using the same strength of current. In the case of cadmium and bismuth I was unable to satisfy myself of the appearance of the spark lines in the arc in a vacuum.

These results may be summarized as follows:

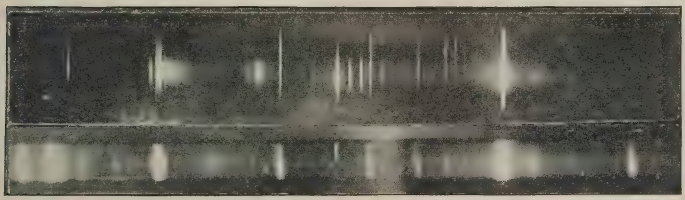
Magnesium.—In the arc in air at atmospheric pressure the arc lines are weakened as the strength of the current is diminished,

while the spark line λ 4481 is increased in intensity. For all strengths of current the arc lines are weakened as the pressure is decreased, and just the reverse is the case with the spark line. The same phenomena occur in hydrogen, but to a more marked degree.

The line λ 4481, when obtained with an arc in a vacuum, does not change its intensity with any variation in the current-strength.

Zinc.—In the arc in air the spark lines λ 4912 and λ 4925 made their appearance when the current was diminished. These lines also appeared very clearly in the arc in a vacuum, while they were absent in the arc in air using the same current-strength.

Since the above observations were completed, an important paper by Professor Crew appeared in the *Astrophysical Journal* for Novem-



1. Spectrum of Magnesium Arc in a vacuum (Current 3 amperes).
2. Showing λ 4481 at cathode.

ber 1904, in which he says that a high E.M.F., rapidly changing, is the essential condition for the production of spark lines in arc spectra. The above results can all be explained by this proposition. For just as hydrogen introduces a greater electromotive force on making and breaking the arc than in air, so also we might expect that the diminution of the density of the dielectric might have a similar effect.

An observation was made which bears directly on the cause of the line λ 4481, and is that it appears principally in the portion of the arc near the negative electrode, as is shown in the spectrum of Fig. 2. This photograph, as well as a number of others giving the same result, was obtained by removing the slit of the spectroscope and placing the arc in its place. For an exposure the arc was only made a second or less at atmospheric pressure with a current of 3 amperes. This result adds further evidence for Crew's suggestion

that spark lines are associated with steep potential gradients, since we know there is a rapid fall of potential at each electrode in the arc.

At atmospheric pressure the free path of an ion is so small that the necessary acceleration for spark lines is only produced close to the electrodes, but as the density of the gas or vapor is diminished, the free paths of the ions becoming longer, one would naturally expect to find the characteristic radiation farther out, and with sufficient exhaustion may reach the entire distance between the electrodes, as is the case in the above results at the pressure of 1 mm. On the same assumption, Hartmann's results as to the increase of intensity of the spark line with decrease of current-strength can be explained, for with a greater current more of the metal electrodes is volatilized, producing an increase of the density.

In the ordinary arc the anode is the hotter, and hence there is a greater density of the vapor in its vicinity. Hence the above hypothesis would account for the greater strength of λ 4481 at the cathode over that at the anode.

In conclusion the author wishes to thank Professor Ames for many suggestions made during the work.

Physical Laboratory,
Johns Hopkins University,
December 1904

Minor Contributions and Notes.

GRANT BY THE SMITHSONIAN INSTITUTION TO THE ASTROPHYSICAL JOURNAL

The editors of the *Astrophysical Journal* again have the pleasant duty of publicly acknowledging the receipt from Doctor S. P. Langley, Secretary of the Smithsonian Institution, of a check for $200 in continuance of his previous liberality. This exceedingly important financial assistance to the *Journal* makes it possible to supply fifty subscriptions to individuals in America and abroad who do not otherwise take the *Journal*, but who, it is hoped, value it.

NOTE ON ADDITIONAL TRIPLETS IN THE ARC SPECTRUM OF STRONTIUM

Photographs of the arc-spectrum of strontium recently obtained by the writer show two unmistakable triplets in the violet which do not appear to have been previously recorded, but which are of special interest on account of their series connection with two of the four narrow triplets to which attention has been drawn by Kayser and Runge. Particulars of the new triplets, and of those having equal frequency intervals already recognized by Kayser and Runge, are given in the accompanying table.

An inspection of the photographs at once suggested that the last four triplets in the list were members of a series of the usual type. The frequency intervals are nearly equal, the intensities gradually diminish as the violet is approached, and all the lines are shaded toward the red. Calculation establishes a series relationship. By taking values of $m=4$, 5, 6, the least refrangible members of the triplets beginning at λ 4892, 4338, and 4087 give the following numerical solution to Kayser and Runge's well-known series formula:

$$n=27646.6-\frac{114374.6}{m^2}-\frac{16160.8}{m^4}$$

Substituting $m=7$, the resulting value of n for the next member of the series is 25305.7, which, taking account of the nebulous character of the lines, is in good agreement with the observed value for the first line of the triplet beginning at λ 3951.

NARROW TRIPLETS IN THE STRONTIUM ARC SPECTRUM

Wave-Length		Intensity and Character	Frequency *in vacuo*	Frequency Intervals
(K. & R.).	5535.01	6	18061.9	
				100.2
	5504.48	10	18162.1	
				59.9
	5486.37	8	18222.0	
	5257.12	10	19016.6	
				100.4
	5229.52	8	19117.0	
				59.7
	5213.23	4	19176.7	
	4892.20	8	20435.1	
				97.7
	4868.92	6 n	20532.8	
				57.7
	4855.27	6 n	20590.5	
	4338.00	6 b^v	23045.8	
				99.2
	4319.39	4 b^v	23145.0	
				58.6
	4308.49	2 b^v	23203.6	
(Fowler)	4087.67	3 b^v	24457.1	
				100.1
	4071.01	2 b^v	24557.2	
				59.2
	4061.21	2 b^v	24616.4	
	3950.96	2 b^v	25303.3	
				100.6
	3935.33	1 b^v	25403.9	
				58.6
	3926.27	1 b^v	25462.5	

n denotes nebulous; b^v, that the line was nebulous on the side toward the red.

Uniting all four triplets in the formula discussed by Mr. Shaw and the writer,[1] the resulting equation for the less refrangible components is

$$n = 27603.5 - \frac{108065.6}{(m+1.817677)^2 + 0.50064} ,$$

in which m has the values 2, 3, 4, 5, for the four lines observed.

Taking $m=3$ in the Kayser and Runge formula, another triplet would be expected with its least refrangible member in the neighborhood of λ 6783, while the second formula, with $m=1$, would predict it near λ 6755. Careful observations in this region, however, have failed to reveal any such triplet, and it would seem that, besides other peculiarities, strontium fails to show this triplet, or has it very feebly developed. In this respect strontium seems to resemble potassium, in which the first doublet of the second subordinate series is so feeble that it has only lately been detected.[2]

A. Fowler.

Royal College of Science, London.
November 1904.

[1] *Astrophysical Journal*, **18**, 21, 1903. [2] *Ibid.*, **20**, 196, 1904.

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SPECTRA OF WEAK LUMINESCENCES

By HARRY W. MORSE

I. THE FLUORESCENCE SPECTRUM OF FLUOR-SPAR

Probably no substance has been more often used for the demonstration and study of fluorescence than the mineral from which the name of the phenomenon was taken. Stokes, who suggested this name,[1] examined the fluorescence of fluorites from various sources, and in his paper "On the Long Spectrum of Electric Light"[2] he gives the results obtained from certain specimens from Alston Moor in Cumberland, England. These crystals were quite pale by transmitted light, of a somewhat brownish-purple color, possessing a strong bluish fluorescence, and phosphorescing with the same blue color for a long time after the removal of the exciting source. Besides this blue fluorescence, which has ever since been described as the one characteristic of the substance, Stokes mentions in the same paper the appearance of a *red* fluorescence of the same crystals under the exciting influence of the spark between certain metallic terminals. That the red color is caused by ultra-violet light Stokes showed by the fact that it disappears completely when a sheet of thin glass is inserted between the exciting source and the crystal, and that it is even weakened by the introduction of a considerable thickness of quartz, as by the use of a quartz condensing lens. He noticed also

[1] *Phil. Trans.*, 1852. [2] *Ibid.*, 1862.

that the red fluorescence is confined to certain strata which are characterized by a deeper color than the remainder of the crystal, and that the light exciting the red color seems to be absorbed by the crystal itself before reaching a great depth, the fluorescence being less intense in the deeper strata. Stokes did not examine the *spectrum* of these fluorescences, but it seems probable that, if spectroscopy had been a slightly more advanced science at that time, he would have carried the investigation farther and discovered the facts about the spectra of these two fluorescences of fluorite, the blue and the red, which are the subject of this paper, and which have been completely overlooked by everyone who has up to the present time worked on the subject of fluorescence.

Fluor-spar is remarkable for the number of different spectra which may be obtained from it under various conditions. Becquerel[1] gives data on the fluorescent color and the spectrum emitted in the phosphoroscope by seven varieties of the mineral of various colors: yellow, green, blue, and purple. Excited by condensed sunlight, a series of bands appeared in the spectrum of the emitted phosphorescence, including a blue-green one which determines the fluorescence color of the mineral under ordinary circumstances of excitation, and others which appear at various rates of rotation of the phosphoroscope and which combine to determine the phosphorescence color at these various rates. Besides these different spectra and the red fluorescence already referred to, which is not excited by daylight, fluor-spar from various sources may give at least three different spectra of thermo-luminescence. Finally, as will be seen later, the spectrum of fluorescence of certain crystals may vary decidedly and sharply with the exciting source.

While examining a series of fluorites from Weardale, England, I was led by the weakness of the emitted light to photograph the fluorescence spectra for the purpose of more accurate comparison. In some of these photographed spectra the "orange band," noticed by many of the observers of the spectrum of fluor-spar, was resolved into what appeared to be narrow bands and *sharp lines*. The exciting source in these cases happened to be the spark between magnesium terminals, and the photographs showed plainly at least four sharp

[1] *La Lumière*, Vol. I, p. 360.

lines not in the comparison spectrum of the spark. It seemed at first possible that light had in some way entered from without at these points, and that an optical or instrumental error was responsible for the remarkable appearance; but a few simple qualitative tests showed that this was not the case, and that the yellow, orange, and red of the fluorescence of this particular crystal of fluorite, as produced under these conditions, is in fact composed in large part of comparatively sharp lines.

The crystals examined were all from Weardale, England, and their physical properties follow:

a) By transmitted light:

No. 1. Colorless. Contained many bubbles and irregularities.

No. 2. Bright green.

No. 3. Yellow. About the color of amber.

Nos. 4–8. Five crystals of various shades of purple and brownish-purple.

b) Fluorescence color (unresolved) and phosphorescence:

No. 1. Weak fluorescence of the usual bluish color.

No. 2. Very strong fluorescence of same color as above.

No. 3. Weak fluorescence. Color same as above.

Nos. 4–8. Strong fluorescence of about equal strength in all. Color the usual bluish.

The phosphorescence color of all of the crystals was of approximately the same color as the fluorescence and varied in strength in about the same way. They all showed long-continued phosphorescence.

c) With direct-vision spectroscope and spark between iron terminals the observed spectra were as follows:

No. 1. Gave weakly the broad blue band ordinarily observed.

No. 2. Gave the blue band very strongly, and in addition to it strong maxima in the green and orange. The two latter maxima were almost completely cut out by introducing a piece of microscopic cover-glass between the spark and the crystal, but not by the introduction of a quartz plate several millimeters in thickness. The blue band is only slightly reduced by the glass and not at all by the quartz plate.

No. 3. Gave the blue band, the green band weakly, the orange band strongly. The two latter were cut out by glass as in No. 2. The

fluorescence spectrum from this crystal is nearly continuous and has approximately the same distribution as that from the filament of an incandescent lamp.

Nos. 4–8. Gave the blue band strongly, the green band weakly, and, in addition to these, a number of apparently sharp lines and bands in the yellow, orange, and red. These were cut out by glass, with the exception of the blue band, but were only slightly weakened by a thick layer of quartz.

It is my intention to return to the green and yellow crystals as soon as possible, but the more evident sharpness of the lines in the spectrum from the purple crystals made their examination easier, and the present paper is devoted to them.

The preliminary qualitative results were obtained by visual work with a direct-vision spectroscope, and they may be briefly stated as follows:

1. The fluorescence spectrum from these purple Weardale fluorites contains many sharp lines, comparable in sharpness with the lines in the exciting source—the spark in air between metallic terminals. These lines disappear almost completely when a thin film of glass is interposed in the path of the exciting light. Microscopic cover-glass (0.17 mm) allows sufficient of the light to pass to cause an exceedingly weak appearance of the lines. A plate of quartz several millimeters in thickness has no appreciable absorbing effect.

Lines belonging to the spectrum of the exciting source, which have reached the spectroscope by reflection on cleavage surfaces and other irregularities inside the crystal, are of course not in the least affected by the introduction of either glass or quartz in the path of the exciting light. The glass plate affords, therefore, an easy method of deciding what lines belong to the fluorescence spectrum and what lines have been accidentally introduced from the spark.

2. The spectrum varies when the exciting source is changed. Even this first preliminary examination showed that the strongest lines in the fluorescence excited by several metals have the same wave-length within the limit of accuracy of the method. But some metals evidently excite the appearance of many more lines than others, and the above statement therefore describes the facts.

3. The spectrum varies from crystal to crystal with the same

exciting source. The entire series of purple fluorites from Weardale showed very similar spectra from the same spark, but later and more exact measurements on them showed distinct differences. Crystals of different color (Nos. 2 and 3, for example) give spectra which are entirely different from those obtained from the purple specimens.

4. No sharp lines appear when sunlight is used as the exciting source. This statement is limited to the experiments which I have carried out, and which do not by any means represent the accuracy desirable. It is very possible that better methods may show the sharp lines in this case also.

5. Only one line has been observed when the arc between carbon poles is used as exciting source.

The small direct-vision spectroscope with which the visual work was done has also been used in the photography of the fluorescence spectra. In spite of its small size, it is well adapted for work of this sort, as the aperture is large (about $\frac{1}{4}$), and good photographs for qualitative examination could be obtained with exposures of less than an hour, using a fairly broad slit-width. For the later more accurate work an instrument was designed with special reference to the photography of spectra from very weak sources of light. This is a spectrograph of the ordinary form, having old Voigtländer portrait lenses of aperture $\frac{1}{3}$ for collimator and objective, and a prism of sufficient size to take the large beam transmitted by these lenses (about 5 cm clear aperture). This type of instrument (which might be provided with old-fashioned portrait lenses of still greater aperture) probably represents very nearly the limit in light-giving power. There are many disadvantages in such an instrument. The dispersion is, of course, very small, and the cone of light is so large that there is very little depth of focus, but the resolving power is great, and under good conditions of working the two sodium lines are perfectly separated, although they are distant only 0.02 mm. Owing to the large cone, the curvature of the field becomes noticeable even over the space of an inch, which is about the length of the spectrum from λ 4000 to λ 7000, and it was found necessary to put the center of the spectrum out of focus in order that the part from λ 5000 to λ 6500, which contains most of the lines under investigation, should be sharp.

The light from the spark was condensed by means of a concave

speculum mirror of about 17 cm aperture and 13 cm focal length. This was mounted for adjustment in all directions and gave good illumination. The spark was from an induction coil for 12 cm spark-length, driven by the 110-volt alternating commercial circuit and provided with a Wehnelt interrupter. The latter was made of large size in order to avoid undue heating during the prolonged exposures. The crystal under examination was mounted on a stand in front of the slit, with screens to prevent the entrance of light not coming from the crystal, which was illuminated in the usual manner from the side by the large cone from the concave mirror. The spark was placed behind the crystal, with an opaque screen between.

Using this prism spectrograph of large aperture, good photographs were obtainable with exposures of from two to eight hours, the time varying with the metal used as exciting source. As most of the sharp lines in the fluorescence lie in the yellow and red part of the spectrum, it was necessary to work with plates sensitive to this region. After some unsuccessful work with various sensitizers, Cramer "Trichromatic" plates were used. They give good results and a fair sensitiveness as far as λ 6500.

In order to test the real *sharpness* of these apparently sharp lines under higher dispersion, a few of the strongest lines in the fluorescence spectrum were photographed with a large aperture concave grating of 163 cm radius and about 2500 lines to the centimeter. With this instrument measurable plates for a few strong lines were obtained with an exposure of six hours, using as exciting source a metal giving a bright fluorescence. A number of the lines in these particular spectra seem to be as sharp as any of the lines in the exciting spark spectrum. The strong line at λ 5732.5, which was the first sharp line observed, was measured on photographs made with the grating with two different widths of slit, and it appears to be as sharp as, or sharper than, any line in the exciting source, which was magnesium. Another sharp line, produced in certain crystals when iron is the exciting source, has been measured with the grating and appears to be equally sharp. On the plates made with the prism spectrograph there are about twenty lines which are as sharp as these two, while many others, not so sharp, are what would be called exceptionally sharp lines to form part of a *fluorescence* spectrum.

In the spectrum produced by certain metals on some of the crystals there are no broad, diffuse portions in the region between λ 5000 and λ 6500, the spectrum containing only lines and narrow bands. Some of the other spectra contain bands which have every appearance of being resolvable into many fine lines with higher dispersion. They run up toward definite sharp heads in a most tantalizing way. The exposure necessary to get these bands on a photograph with the grating would run up into days, even with a slit of some width.

There have been measured in the spectra from these purple fluorites from Weardale some 200 lines and bands, lying between λ 4700 and λ 6400. A number of strong lines have been observed farther toward the red, but no visual wave-length measurements have as yet been made on them. The dispersion of the spectrograph is so small, especially out in the yellow and red end of the spectrum, that the measured wave-lengths given in the following tables have an accuracy not greater than 2 to 3 tenth-meters. It is therefore not possible to decide many questions of great importance about the identity of lines occurring near one another in various spectra. No attempt has been made to decide these questions from the data at hand, and the wave-lengths have been given as they were in the laboratory notes taken when they were measured.

The tables given below contain data on the fluorescence spectra of two crystals of purple fluor-spar under the exciting influence of several metallic sparks. One of these is a natural crystal, and the other has had its faces polished to remove the roughness and irregularities which reflect light from the spark into the slit of the spectrograph. As will be seen from the tables, these two crystals give very different spectra of fluorescence with the same exciting source, the natural crystal showing lines peculiar to itself and the polished one lines representative of the other four crystals examined—Nos. 5, 6, 7, and 8. Photographs of the fluorescent spectrum from these four crystals taken before they were polished show no differences from the later ones taken after polishing. The latter are comparatively free from spark lines which have been accidently reflected into the slit, and they have therefore been used for the more accurate measurements.

EXCITING SOURCE, MAGNESIUM SPARK

Crystal No. 4	Crystal No. 5 (Fig. 1)
5283 (5) sharp	5285 (5) sharp
5337	
5373	
5405	
5435	
5470 Rather diffuse maxima.	
5500	
5580	
5612	
5670	
5713 (3) sharp	5715 (2) sharp
5733 (100) sharp	5736 (100) sharp
5770	
5800 (10) sharp	5803 (10) sharp
5838 broad line	
5850 (2) sharp	
5885 unresolved band	
5915 diffuse maxima	
5953	
6055 (4) quite sharp	
6067 (2) sharp	
6109 (2) sharp	
	6140 (10) sharp
6195 diffuse maxima	
6210	
6250 (3) sharp	
6350 (5) sharp	

The exposure for the two crystals was the same—about four hours—but the diffuse lines which have come out so strongly in crystal No. 4 do not appear in measurable intensity in the crystal No. 5 with this exposure. There are faint indications of the bands in the latter, but they are not resolved or measurable.

As may be seen in the plate (Fig. 1), the spectrum of magnesium contains several strong sharp lines, including one of especial strength at λ 5733–λ 5736. The spectrum also contains a large number of weaker lines and bands which do not appear on the plate, but which have been measured and entered in the table of wave-lengths.

The spectra produced in different crystals by magnesium as exciting source do not appear to differ very noticeably in the strong lines within the limit of accuracy of the measurements. In the spectrum from crystal No. 5 there appears one strong sharp line at λ 6140 which does not appear in the fluorescence of the other crystal.

The effect of introducing inductance into the secondary circuit of

the spark is to lower the general strength of the exciting light, and therefore to greatly lengthen the exposure. Although the air lines appear to be completely cut out by the inductance used, the strong lines appear with the same sharpness and the same relative intensities as without the inductance (see Fig. 2). The exposure was insufficient to bring out the weaker lines or bands. It would seem that the air lines have nothing to do with the appearance of the strong lines in the case of magnesium, and the same proof has been obtained for other metals used as exciting source.

EXCITING SOURCE, IRON SPARK

Crystal No. 4 (Fig. 5)		Crystal No. 5 (Fig. 3)	
4747		5256	
5168		5287	diffuse lines.
5236		5351	
5270	diffuse lines	5416	sharp edge of band
5336		5425	
5374		5447	
5400		5481	(3) sharp
5434		5513	
5468	(3) sharp	5553	sharp end of band
5510	unresolved double?	5582	edge of band
5534		5619	(5) maxima in band
5574		5672	
to	band	5696	
5612		5715	(20) sharp
5667		5727	(5) sharp
5712		5737	(20) sharp
5732		5777	diffuse lines
5767	diffuse lines	5811	
5807		5851	(5) quite sharp
5838		5890	(3) quite sharp
5870		5922	(3) quite sharp
5913		6070	(15) sharp
6059	(5) sharp	6240	(3) sharp
6200	(3) sharp		

From the five purple crystals examined there have been obtained two entirely different spectra of fluorescence. These are to be divided into the spectrum from crystal No. 4, and that from the other crystals. Crystal No. 4 gives a spectrum composed of a large number of diffuse but quite narrow lines, with a few sharp strong lines, while the other crystals all give the same spectrum, containing a number of strong sharp lines and an entirely different arrangement of the weaker lines and bands from that in crystal No. 4.

The introduction of inductance into the secondary circuit has no effect on the position or relative strength of the strong lines. Since the intensity of the light from the spark is far less reduced in iron than in magnesium, the exposure required to photograph the spectrum is not very much longer than without the inductance.

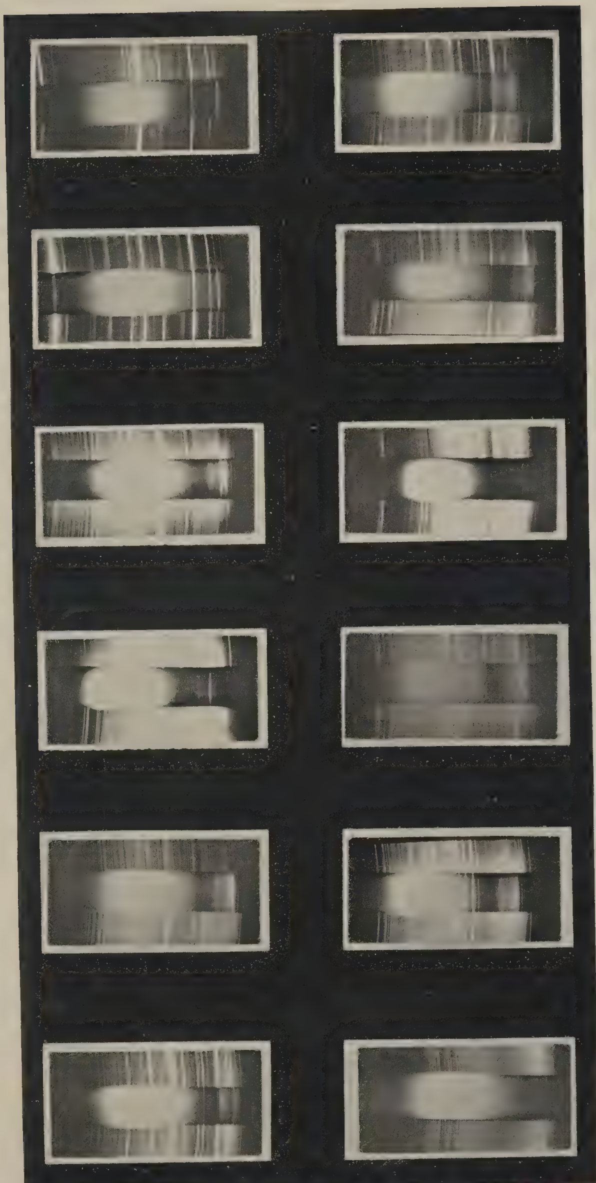
In the plate, Fig. 3 shows the appearance of the fluorescence spectrum from the crystal No. 5 and Fig. 5 the spectrum from crystal No. 4. Fig. 4 shows the spectrum produced when inductance is introduced into the discharge circuit, the crystal in this case being No. 5.

EXCITING SOURCE, CADMIUM SPARK

Crystal No. 4 (Fig. 7)	Crystal No. 5 (Fig. 6)
5394, 5428, 5465, 5498 } diffuse lines	5403 (1) sharp
5527 band head?	5408 (2) sharp
5571, 5598 } band	5420 (10) sharp
5696 diffuse toward red	5453, 5468, 5483 } underlying band below head
5759 diffuse	5508, 5516, 5535, 5553 } underlying band below head
5815, 5832 } rather sharp lines	5568 diffuse
5865 to 5902 } unresolved lines?	5588, 5612, 5618 } head
6048 (10) sharp	5711 (20) sharp
6250 (3) sharp	5723 (10) sharp
	5737 (7) sharp
	5770 diffuse
	5843 unresolved?
	6030 (15) sharp

The same differences between the spectra from the two crystals appear when cadmium is used as exciting source as have been already noticed under magnesium and iron. Fig. 6 gives the appearance of the spectrum from the crystal No. 5 and Fig. 7 that for the crystal No. 4. There are several very sharp and strong lines in the spectrum

PLATE VII



. *Mg* Spark
Crystal No. 5

. *Mg* Spark
No. 5. Inductance

;. *Fe* Spark
Crystal No. 5

4. *Fe* Spark
No. 5. Inductance

5. *Fe* Spark
Crystal No. 4

6. *Cd* Spark
Crystal No. 5

7. *Cd* Spark
Crystal No. 4.

8. *Al* Spark
Crystal No. 5

9. *Al* Spark
No. 5. Inductance

10. *Al* Spark
Crystal No. 4

11. *Zn* Spark
Crystal No. 4

12. Arc

Spectra of Weak Luminescences

shown in Fig. 6, notably the triplet λ 5711–λ 5737. The lines of this triplet are of the same order of sharpness as the lines of the comparison spectrum.

EXCITING SOURCE, ALUMINIUM SPARK

Crystal No. 4 (Fig. 10)	Crystal No. 5 (Fig. 8)
4757	4753 (3) sharp
4931	4914 (2) sharp
4961	5340 (1) sharp
5021	5378 (2) sharp
5260	5408 (2) sharp
5289	
5318 rather diffuse lines	5442
5350	5451 underlying band below
5381	5498
5420	5543
5450	
5490	5570
5532	5604 underlying band below
	5617
5589	5658 underlying band below
to unresolved band	5672
5636	
5679	5710 (20) sharp
to unresolved band	
5732 (5) sharp	5720 (8) sharp
to	
5780	
to unresolved band	5732 (3) sharp
5953	5750
	5767 underlying band below
6081 (5) sharp	5774
6100 (3) sharp	5810
	5833 underlying band below
	5842
	5867 underlying band below
	5905
	6020 (3) sharp

Aluminium as exciting source gives for different crystals differences in the fluorescence spectra of the same sort as those already observed in the preceding metals. Crystal No. 4 gives a spectrum containing more diffuse lines, and crystal No. 5 shows lines of greater strength and sharpness.

It will be noticed that the group at λ 5710–λ 5732 agrees nearly with groups in the spectra produced by *Mg*, *Cd*, and *Fe*, with a slight shift in wave-lengths as compared with the last two metals. I have repeated the measurements on all of these spectra without convincing

myself that this shift is due to errors of measurement, but the accuracy in this part of the spectrum is so small that the possibility of such an error has not been eliminated.

Fig. 8 shows the appearance of the spectrum from crystal No. 5 and Fig. 10 that for crystal No. 4. Fig. 9 shows the effect of introducing inductance into the spark-gap, the crystal being one with polished faces. No difference whatever seems to be introduced and the conclusion is that the air lines do not play any important rôle in the excitation of the fluorescence.

EXCITING SOURCE, ZINC SPARK

Crystal No. 4 (Fig. 11)

5237 (3) sharp	5670 (3) sharp
5326 (2) sharp	5696 diffuse
5361 (3) sharp	5718 (2) sharp
5398 (10) sharp	5751 diffuse
5430	5802 (3) sharp
5460	5832 (10) sharp
5485 to 5528 unresolved band	5850 to 5885 unresolved
5570	6045 diffuse
5598 appears to consist of several lines	

Fig. 11 shows the appearance of the fluorescence of this crystal under the exciting influence of the spark between zinc terminals. There appear under these circumstances a large number of sharp lines, more than this crystal shows for any other metal.

EXCITING SOURCE, MERCURY SPARK

Crystal No. 4

4926, 4962, 5010, 5058, 5115, 5159, 5225 diffuse lines	5482, 5533 diffuse lines
	5610
	5678 to 5963 unresolved

There are no sharp lines in this fluorescence spectrum.

EXCITING SOURCE, TIN SPARK

Crystal No. 4	Crystal No. 5
5733 (2) sharp	5720 (2) sharp
5835 to 5885 unresolved	5743 (2) sharp
	5760 (2) sharp
6046	

Tin as exciting source gives rise only to a weak fluorescence. The differences between the two crystals are as plainly marked as in the cases already considered.

The spark between lead terminals gives no lines of intensity sufficient to permit of photography or measurement, and the arc between ordinary carbon terminals gave only one line at λ 5733, the line appearing with both crystals (Fig. 12).

In all of the spectra examined, the blue band, broad and diffuse, is present, extending from about λ 4000 to λ 5000. The following diffuse bands underlying the lines given in the tables, have also been observed:

Iron: band from λ 5530 to λ 6000.
Cadmium: band from λ 5330 to λ 5980.
Zinc: band from λ 5320 to λ 5940.
Tin: band from λ 5460 to λ 6110.

Comparison of sharp lines in crystals under excitation by various metals:

CRYSTAL NO. 4

Mg	*Fe*	*Cd*	*Al*	*Zn*	*Sn*	Arc
				5237		
5283						
				5326		
				5361		
				5398		
	5468					
				5670		
5715				5718		
5733			5732		5733	5733
5800				5802		
				5832		
6055	6059	6048				
6067						
			6081			
			6100			
6109						
	6200					
6250		6250				
6350						

The table below contains the wave-lengths of the sharp lines of the previous tables. It will be seen that there are a few lines which appear to be common to several exciting metals. The most evident example is the line near λ 5735. This is a strong sharp line in the following spectra: from crystal No. 4 with *Mg*, *Al*, *Sn*, and the arc

CRYSTAL NO. 5

Mg	*Fe*	*Cd*	*Al*	*Zn*	*Sn*	Arc
			4753			
			4914			
5285						
			5340			
			5378			
		5403				
		5408	5408			
		5420				
	5481					
	5619					
5715	5715	5711	5710			
		5723	5720		5720	
	5727					
5736	5737	5737	5732			5733
					5743	
					5760	
5803						
	5851					
	5890					
	5922					
			6020			
		6030				
	6070					
6140						
	6240					

as exciting source; from crystal No. 5 with *Mg, Fe, Cd, Al,* and the arc as exciting source. The differences in the measured wave-lengths are about of the order of the error in this part of the spectrum. Other coincidences are: crystal No. 4: λλ 5715–5718 in *Mg* and *Zn,* λλ 5800–5802 in the same metals, λλ 6055–6048 in *Mg* and *Cd,* λ 6250 in the same metals. In crystal No. 5 the strong lines at λλ 5710–5715 in *Mg, Fe, Cd, Al,* and λλ 5720–5727 in *Fe, Cd, Al, Sn,* appear to be real coincidences.

The facts exhibited in the above tables may be summarized as follows:

1. The fluorescent light excited in a crystal of fluor-spar by the light from certain metallic sparks may show in its spectrum many sharp lines and narrow bands. It would seem from the facts at hand that the entire fluorescence spectrum contains a *very great* number of these sharp maxima, a part of which are excited by the light from one spark, another part by another spark, etc., and that it must, in fact, be considered the sum of all the lines that are excited by all the different sparks.

2. Certain of these maxima *appear* to be common to the fluorescence spectra excited by different sparks. The want of accuracy in the measurement of the wave-lengths (2 to 3 tenth-meters) prevents a more definite statement of this important point.

3. Certain of these maxima are evidently peculiar to the light excited by a single metal, as no small error in the determination of the wave-lengths could account for the different distribution of the strong lines in the various spectra produced in the same crystal by different exciting sources.

4. The fluorescence spectrum may vary from crystal to crystal, not only in minor points, but even in the strongest lines.

5. Metals with a strongly marked ultra-violet spectrum excite extended fluorescence spectra.

As is shown directly by the effect of glass and quartz plates, the exciting light for these lines lies between λ 3000, where glass absorbs almost completely, and λ 2000, where quartz begins to show absorption. It is therefore to be expected that metals having strong lines in this region will excite the strongest fluorescence. Magnesium has not a large number of lines in this region, but the lines belonging to it are very strong ones, and the fluorescence spectrum excited by its spark contains as many lines as any of the spectra observed. The metals which excite fluorescence lines of shortest wave-length are, however, iron and aluminium, both of which show strong lines over the region from λ 3000 to λ 2000. Lead, a metal with a comparatively weak ultra-violet spectrum, shows no fluorescence lines whatever.

6. The strong lines in the fluorescence spectra lie between λ 5700 and λ 6400. The whole spectrum excited by a metal like iron extends from λ 4000 to about λ 7000, the part from λ 4000 to λ 4800 being covered by the broad blue band which is excited by light of not much shorter wave-length. The part from λ 4800 to λ 5700 contains many narrow bands and some rather weak sharp lines, and the part from λ 5700 to λ 7000 contains the strong sharp lines.

THE SOURCE OF THE FLUORESCENCE LINES

All the results obtained so far, which have bearing on the mechanism of these phenomena, are of negative character. As this is merely a preliminary note on what it is hoped will prove a more extended

examination of the matter, it may be best to summarize the data at hand.

1. The lines so far measured in the fluorescence spectra of these crystals do not appear to belong to any known substance. The first measurements on the strongest line suggested the spectrum emitted by yttrium compounds when fluorescing in a vacuum tube under the influence of the cathode discharge. The strongest line in the fluorescence spectrum excited by several metals falls on the "citron band," for the cause of which Crookes searched so long, within the limit of accuracy of the measurements. Humphreys[1] has recently shown that yttrium is a very common and perhaps a universal impurity in fluor-spars from many localities. The spectra were therefore carefully compared with Crookes' tables for the lines of the yttrium luminescence, but there were no other even approximate coincidences of strong lines.

2. Although certain fluorescence spectra do vary with the exciting source, shortening or lengthening as the wave-length of the exciting light is increased or diminished, a total change in the distribution of sharp lines over a spectrum, due to a change in the exciting source, is something beyond our ordinary experience of spectrum production.

3. The possibility of optical resonance has been examined, with wholly negative results. Since the lines in the fluorescence spectrum are so sharp, it seemed at first possible that a definite relation between sharp spark lines (in the region from λ 3000 to λ 2000) and the fluorescence lines might be established. Magnesium, for example, has the following sharp strong lines in its fluorescence spectrum: (crystal No. 4) λ 5732, λ 5800, λ 6056, λ 6110, λ 6195, λ 6350. The strongest lines in the *Mg* spectrum between λ 3000 and λ 2000 lie close about λ 2800, with others at λ 2852, λ 2929, λ 2937. No relation between the oscillation-frequencies of spark lines and fluorescence lines has been found. A strong line lying between λ 5730 and λ 5740 is characteristic of the fluorescence spectra produced in the polished crystals by *Fe, Al, Cd, Mg, Sn,* and the ultra-violet spectra of these metals are so very different that it is hardly possible that there should be a simple relation between a strong line in all of these spark spectra and a line of the fluorescence spectra lying within the limits given. Since

[1] *Astrophysical Journal*, **20**, 266, 1904.

certain air lines might be common to all of these metals, and it is possible that they might be the excitant giving common fluorescence lines, especial interest attaches to the spectra produced with inductance in the secondary discharge circuit. The lines of the air spectrum are quite completely cut out by inductance within the region of the comparison photographs, but this can hardly be taken as proof that they are cut out in the ultra-violet as well. Our knowledge of the air lines in the region between λ 3000 and λ 2000 is not very perfect, but the fact that the introduction of inductance in no case alters the relative strength of fluorescence lines may be taken as evidence that the metallic lines are the main exciting source. The possibility of optical resonance is made still more improbable by the fact that the spectrum varies sharply from crystal to crystal with the same exciting source.

4. These new lines of fluorescence may be connected with an impurity in the crystals. All of the crystals which give the sharp lines are colored, and the colored parts are in layers or *strata*. The fluorescence which gives the sharp lines is either confined to these strata or is much stronger in them than in the other parts of the crystal. So far as I know, this stratification of the fluorescing part of fluorite was first noticed by Sir David Brewster.[1] It was also noticed by Stokes[2] as being the source of the red "fluorescence," but, as he did not examine the spectrum, he did not observe the lines produced in the fluorescence of the colored strata.

5. Whatever the source of the fluorescence, it is completely removed by heating the crystal to a temperature above 300° C. Crystals of the purple fluorite when so heated as to lose their power of giving the red fluorescence change their external appearance and become milky and opaque in the strata which were previously colored and which gave most strongly the sharp lines of fluorescence; while the strata which were previously colorless and which did not give the sharp lines retain their transparency. On exposing a crystal which has been so heated to the spark it may again be made to give the *blue* band of fluorescence, but the red fluorescence which yields the sharp lines is not regenerated.

6. The change in the appearance of the fluor-spar on heating

[1] *Pogg. Ann.*, **73**, 531, 1848. [2] *Phil. Trans.*, 1862.

appears to be due to the crushing effect of the expansion of inclusions which were present in the mineral. Examination of thin sections of the mineral shows layers or sheets of inclusions scattered through it, the hollow containing in each case about three-fourths of its volume of liquid, while the remaining space is filled with a bubble of gas. The crystals which had been rendered milky by heating showed on the surface evidence that the included liquid and gas had burst through the inclosing walls and shattered the crystal in all directions. This does not prove that the same effect has been brought about in the deeper parts of the crystal, but the matter seems to deserve further examination.

7. Even though it be admitted that the fluorescence is due to an impurity of a liquid or gaseous nature contained in the inclusions of the mineral, we are brought no nearer to an explanation of the facts connected with the appearance of the *sharp lines* of fluorescence.

The investigation will be continued along two lines: an examination of the spectra under conditions of greater accuracy, and an examination of the substances included in the naturally occurring mineral.

My hearty thanks are due to the Bache Fund of the American Academy for a grant which has been of great assistance in carrying out this research.

Jefferson Physical Laboratory,
Harvard University,
January 1905.

THE SOLAR ORIGIN OF TERRESTRIAL MAGNETIC DISTURBANCES

By E. WALTER MAUNDER

Early in the year 1904 I communicated to the Royal Astronomical Society two papers on the "Great Magnetic Storms of the period, 1875–1903." The first paper treated in detail the nineteen greatest storms of the period, and gave an account of the state of the Sun's surface at the time of each. It appeared from the comparison that there was a real connection between large sun-spots and great magnetic storms, and a real, but only rough, connection between the size of the spot and the intensity of the storm; the area of the spot-group being by no means an exact index of the degree or intensity of the magnetic disturbance. The second paper suggested a possible explanation of the obvious fact that, though, if we consider a number of instances, there will *on the average* be a distinct approach to a definite relation between the extent of a spot, and the violence of the storm associated with it, yet such a relation does by no means hold good in every individual case. The suggestion made was that it was conceivable that the solar action, giving rise to our magnetic disturbances, was not equally great in all directions, but was most intense in a definite direction, and the analogy of the long rays of the solar corona was appealed to as an example of an action like this in its directive character.

At the time of writing these two papers I was able only to adduce as a proof of my suggestion that we actually found, at the moment of commencement of the nineteen great storms examined, that the most important spot on the Sun was always within a restricted area of the surface. If the influence of the spot were exactly equal over the whole sphere of which it was the center, it is difficult to understand why this relation should have shown itself.

I am now in a position to give a much fuller demonstration that the solar action is directive in character. On the completion of my paper on the nineteen great storms, I tried to extend the same method to all the disturbances represented in the plates of the

Greenwich Magnetic Results from 1882 onwards. These were about 310 in number; when those were excluded in which the greatest amplitude of movement in declination was under 20′, the number left was 276. The detailed comparison of these with the groups of sun-spots on the disk of the Sun at the time of their appearance proved a laborious and unfruitful task. There were a large proportion of cases in which a very plausible argument could be offered in favor of a connection between the disturbance and the particular spot-group. There were yet more instances in which the spot-groups present were too numerous for one or other to be singled out as certainly associated with the disturbance. There were some instances when there were no spots at all on the Sun, or those seen were so insignificant that it seemed absurd to assign any influence to them. In all, the history of over 800 spot-groups was investigated, and though a general correspondence between the spots and the disturbances appeared to be clearly indicated, the individual discordances remained very perplexing.

The next step was an attempt to ascertain if any better correspondence could be found by limiting the inquiry to the spots of either the northern or the southern hemisphere. The faculæ were next tried, then the prominences, and these were tested in several different ways; first the prominences as a whole, then the prominences of either hemisphere, then those within 20°, first of one pole and then of the other, and of the two combined; and still no progress was made. There was a general resemblance, except in the case of the polar prominences, in the very broadest features of the curves, but none reproduced the details of the curves of magnetic disturbances.

At this stage, while looking over the list of the 276 disturbances which I had scheduled, my eye was caught by the four catalogued at the end of 1886, since they succeeded each other at very nearly equal intervals of time, and in the following year a similar set of four presented themselves. The following little table gives the times at which they commenced.

It was clear at once that the mean period indicated by these two sets of disturbances was none other than that of the mean, synodic rotation period of the Sun as derived by Carrington and

Reference Number	Class of Storm	Date of Commencement	Interval	Mean
75	Active	1886 Sept. 9^d 13^h		
76	Active	Oct. 6 17	27^d 4^h	
77	Moderate	Nov. 2 15	26 22	27^d 8^h
78	Active	Nov. 30 13	27 21	
81	Moderate	1887 Aug. 1 11		
82	Moderate	Aug. 28 20	27 9	
83	Very Active	Sept. 25 16	27 20	27 9
84	Moderate	Oct. 22 15	26 23	

others from observation of sun-spots, and I was at once reminded that, in my paper on the nineteen great magnetic storms, sixteen had synchronized with a large or very large group of spots, but the other three had synchronized, not with a large group, but with the *return* of a group which had been large in the preceding rotation. It therefore occurred to me that it would be well worth while to take out the heliographic longitude of the center of the Sun's disk for the times of the commencement of each of the 276 disturbances of my table.

The relations brought out by this computation were most striking. No fewer than thirty-six sets were noticed in which a disturbance in one rotation was followed in the next rotation by another when the same heliographic longitude was again on the center of the Sun's disk. Of these sets twenty-three were pairs, eight were triplets, four extended to a fourth consecutive rotation, and one to a sixth. Besides these, there were sixteen cases in which the interval was not one rotation, but two, so that nearly one-half of all the items in the catalogue were included in one or other of these sequences. It should be further noted that in a large proportion of these cases not only did two disturbances occur at the interval of one or two solar rotations, but no disturbance occurred in the interval. When higher multiples of a rotation period than two were included, it was found that more than three-fourths of the whole number of disturbances catalogued could be grouped in some longer or shorter sequence. In short, the solar rotation period was stamped upon the whole series of disturbances under consideration from beginning to end. It is not too much to say that if the solar disk had

never been diversified by a single marking, if we had never seen a sun-spot, a facula, or a prominence, yet, if the spectroscopic method had made known to us the length of the solar rotation period, the evidence presented by these magnetic disturbances would have proved beyond dispute that they had their origin in the Sun.

This is the first and most important conclusion to which we are led. The suggestion that has been made that sun-spots and magnetic disturbances may be joint effects, both produced by some body or bodies moving in interplanetary space, is finally disproved. The exciting cause of the terrestrial magnetic disturbances is in the Sun, not exterior to it.

Further, the cause, whatever its nature, is not general to the whole surface of the Sun, but is local to certain regions. The solar rotation period could not evidence itself if this were not the case, and if the area whence the magnetic action took its rise were not fairly limited and defined.

The next result is the one which I offered as a suggestion nearly a year ago. This solar "magnetic action,"[1] whatever its nature, can not be radiative like light and heat, equally in all directions. This is, indeed, suggested by the extreme suddenness with which so many storms, and all the greater ones, commence. But so long as it was not recognized that the disturbances manifested the solar rotation period, so long it was possible to conceive of each storm as answering directly to a fresh explosion of energy on the Sun, the time of commencement of the storm representing precisely the time of the actual solar explosion, corrected only for the interval necessary for the effect to travel to us. But it is not possible to conceive that such solar explosions should systematically take place at intervals corresponding to the synodic rotation period.

[1]In speaking of the Sun's "magnetic action," and of "magnetically active" areas upon its surface, I am not in the least desiring to make any physical assumption whatsoever, but am using these expressions merely to indicate that the exciting cause of our magnetic disturbances—whatever its character and mode of operation—arises from the Sun, and from limited areas of it. And in using the words "exciting cause," I am leaving the question entirely open as to whether the Sun actually supplies the energy manifested in these storms, or merely brings about its release. These are not questions within my province; nor, if they were, do they lie within the scope and purpose of my present paper.

It follows that the sudden and definite commencement of the disturbances can only be explained by the collision between the Earth and a well-defined stream; a stream rising and being continually replenished from a limited area on the Sun's surface, and thus appearing to us to travel with the speed of the solar rotation. In other words, we are not struck by the advancing face of a spherical wave, spreading out from the Sun in all directions, but the Earth is overtaken in its orbit by a fairly well-defined stream.

The fourth point is a very interesting one. The various disturbances do not all give precisely the same rotation period; they show a range, though not a very wide one; the mean daily angular motion which they indicate ranging from 14° 32′ to 13° 39′, values agreeing exceedingly closely with those found by Carrington for the equator and for latitude 30°. In other words, the "magnetically active" areas of the Sun are confined to zones the rotation periods for which correspond to those of the zones where sun-spots most congregate. And it has already been shown that in certain instances there can be no reasonable doubt of the direct connection between certain individual spots and certain individual storms.

But it follows at once from what we have already seen as to the directive nature of the Sun's magnetic action, that many spots must fail to exercise any sensible influence upon terrestrial magnetism because in their cases the line of direction does not intercept the ecliptic. The average duration of the disturbances in my catalogue was thirty hours. This would correspond to 16°.5 of heliographic longitude, and would imply that the mean diameter of the stream lines was not greater than 20°, if we suppose them circular in section. We might expect, therefore, that a considerable majority of such stream-lines would completely fail to strike the Earth.

But while we ought thus to have many instances of important spots which produce no effect upon our magnets, there seems clear proof that the magnetic action may continue for long after the spots have ceased to be visible to us. A very striking instance occurred in 1889. As will be seen from the table below, an active disturbance was registered at Greenwich on July 17. Twenty-seven days later another occurred, on August 13. Again twenty-seven days,

and a moderate disturbance took place on September 8, and similarly on October 5, November 1, and November 26; the interval steadily diminishing at each successive return. It is not possible to look at this record, obtained at a time when disturbances were rare, without being convinced that these six were not separate and distinct outbreaks of energy, having no connection with each other, but were indeed returns of one and the same disturbance. If so, they form as a series by far the most important magnetic event of the year, and we naturally inquire whether there was any phase of sun-spot activity to correspond. There was. The largest group of the year synchronized in its second and third returns with the disturbances of July and August, while the spot-group third in importance in the year took its origin shortly before the July disturbance, and synchronized with the one of August at its return. It is, of course, open to question whether we ought to associate the magnetic disturbance with the one group or with the other, or with the joint action of both; but it is striking that the most important and most long continued magnetic disturbance of the year should thus have synchronized with the most important spot-groups. But the spot-groups did not return with the third return of the magnetic disturbance, so that the latter was felt for four successive rotations after the spot-groups had ceased to be visible to us.

Reference Number	Class of Disturbance	Date of Commencement	Longitude of Sun's Center
104	Active	1889 July 17^d 4^h9	57°.0
105	Moderate	Aug. 13 5	60.0
106	Moderate	Sept. 8 23	66.5
108	Moderate	Oct. 5 17	73.4
111	Active	Nov. 1 6	83.4
112	Active	Nov. 26 15	108.8

Perhaps the most striking instance of the return of a magnetic storm with the return of a spot was furnished by the great group of February 1892, much the largest group of the last thirty years. The mean longitude of this group, during its apparition in February, when it attained its greatest area, was 255°.7. The great magnetic storm began when it was 17°.5 west of the central merid-

ian; that is to say, when the longitude of the Sun's center was 238°.2. When the group returned in March, it had very greatly diminished in size; its mean longitude in this apparition was 250°.3, and the second great magnetic storm commenced when it was 17°.1 west of the center of the Sun, that is to say, when the longitude of the Sun's center was 233°.2. The correspondence therefore between spot and storm was exact to four-tenths of a degree of solar longitude, or less than three-quarters of an hour of time; a striking correspondence when it is remembered that the group was some 24° of solar longitude in length at its greatest development, and took forty-four hours to cross the central meridian.

It is perhaps worthy of note that in the following year, 1893, magnetic disturbances occurred in five rotations out of the thirteen, when this same meridian (235° ±) came to the center of the disk. The most striking of these synchronized with a revival of activity in the same region of the Sun; two groups of sun-spots forming in July 1893 within the area covered by the great group of February 1892. It must not be supposed that whenever a spot broke out in this region a marked magnetic disturbance always accompanied it, or that when a disturbance was experienced at this particular meridian spots were always seen to correspond. But the intermittency in the activity of sun-spots and of disturbances have the same general character, though that activity is by no means always manifested at the same time in the two phenomena. One other relation calls for notice. There seems to be a distinct tendency for magnetic disturbances to occur at the end of thirteen or fourteen rotations; that is to say, as nearly as possible at the end of a solar year. The most striking case of this is afforded by a comparison of the years 1899 and 1900. My catalogue contains only three disturbances in the latter year. As will be seen from the following table, in each case a disturbance, almost exactly at the same solar longitude, occurred just thirteen rotations earlier.

There is no difficulty in conceiving the manner in which the solar action giving rise to our magnetic storms may be conveyed to us. The corona has been at some trouble, these many years past, to visualize for us an action which is at least analogous to that in question. For myself, the first hint of the idea came with

Date of Commencement	Longitude of Sun's Center	Date of Commencement	Longitude of Sun's Center
1899 Jan. 28^d 19^h	172°.2	1900 Jan. 19^d 18^h	153°.7
Mar. 23 15	183.0	Mar. 13 2	184.5
May 15 13	204.1	May 5 3	204.4

my first sight of a total solar eclipse in 1886. From that time I have never had the slightest doubt but that at least the polar plumes are strictly analogous to the tails of comets; that is, that they consist of very minute particles driven away from the Sun by some repulsive force; whether that might be electrical, or due to the pressure of radiation or to some other cause, is not at this point a matter of importance. In 1898 I was led, from the examination of the photographs taken by the expedition of the British Astronomical Association at Talni, India, to recognize that the synclinal structures were also formed by a repulsive action; Mr. Thwaites's negatives showed the formations at the base of those structures; Mrs. Maunder's showed those structures drawn out into long rod-like rays at the apex. True, none of the actual rays then photographed could have encountered our Earth, their inclination to the ecliptic being too considerable; but, having seen so clearly upon the photographs the intimate building up of those rays, it became impossible to contend that similar rays might not from time to time be formed which would actually overtake us.

It will be seen that the relation, brought out by my inquiry, is of the very simplest; most easy to detect and to demonstrate; it is simply that our magnetic disturbances show a very strongly marked tendency to recur with the return of certain definite meridians of the Sun to the center of the disk. But the consequences are revolutionary. First of all, it is clear that our magnetic disturbances do have their origin in the Sun, and not in any interplanetary corpuscles, or in the varying electrical conductivity of extra-solar space if this be conceived as varying independently of solar action. Next, the solar magnetic action, giving rise to these disturbances, is not from the whole surface, but from certain restricted areas. These areas are clearly connected with sun-spots, since the disturbances occur at intervals correspond-

ing to the rotation period of the Sun, as determined by sun-spots, and to the special rotation periods of the chief sun-spot zones. Third, these areas can be magnetically active both before a spot has formed and after it has disappeared. Their activity is, in the general way, most easily and continuously manifested to us by the presence of sun-spots, and by the changes which they undergo; but sun-spot formation can be considered only one phase of their activity, and possibly not the most important and significant one. Lastly, the action from these special areas is not radiative, like light and heat, but directive, along narrow, well-defined streams.

OBJECTIONS

Several difficulties have occurred to me in the course of my inquiry. The first is connected with the very small area which the Earth presents to the Sun. Unless the stream-lines from a spot region are of very considerable cross-section, it would seem to be most unlikely that any one of them should strike the Earth; whereas a large majority of very great sun-spots are associated with considerable disturbances; and, moreover, these sun-spots are often in very high latitudes, and may pass the center of the disk at a distance of 30° or even 35° from it. Again, some of the sequences, in which the disturbances appear to run, extend more or less intermittently through the entire year, or at any rate from March to September, or September to March; that is to say, it appears to be a matter of indifference to them as to whether the latitude of the center of the Sun's disk has its greatest southern or its greatest northern value. A further difficulty lies in the fact that, though on the average a magnetic disturbance will commence when the sun-spot with which it would seem to be associated has passed the central meridian by several hours, yet occasionally it begins before the spot has reached the center.

These and similar difficulties are no doubt serious, and at present I am not in a position to do more than suggest partial and possible explanations. In the first place, if we may be guided by the coronal forms, it is clear that the solar stream-lines need not be truly radial. Of the four great rod-like rays photographed during the eclipse of 1898, one appeared almost tangential to the Sun's limb, one

was inclined, and two appeared to be radial. Whether they were really radial or not we cannot say, for, while a streamer which is truly radial, must appear to be so from whatever position it is viewed, the converse does not hold good. We have therefore no *a priori* right to assert that the stream-line from a spot in high latitude, or from one that has not yet reached the central meridian, might not encounter the Earth.

The difficulty of the frequency of our magnetic storms may be met in two ways. It is possible that the solar streams tend to diverge after a certain distance from the Sun, so that they cover an area of many degrees by the time they have reached the Earth's orbit. The other explanation, which is more in accordance with what the forms of the corona seem to indicate, is that, from one cause or another—possibly as an indirect effect of the solar rotation—there is a tendency in all these stream-lines to be directed toward the Sun's equator. It seems improbable that the stream-lines can have any very great cross-section at the Earth's orbit. The mean duration of the disturbances in my catalogue—thirty hours—implies, as stated above, a diameter of 20°. But this is to suppose, what is most unlikely, that the disturbance ceases the instant the stream-line has entirely passed the Earth; it is far more probable that the impact of the stream would set up an excitement, which would by no means soon come to rest. Indeed, I think that the examination of the trace of a typical disturbance suggests that this is exactly what does occur; that there is a sudden dislocation of the magnetic equilibrium, continuing only for a relatively short space of time, and after the exciting cause has passed, the magnets slowly recover their usual stability. In this case we might regard the average diameter of a stream-line as probably not more than two or three degrees.

A third suggestion has been made which would effectually meet this difficulty, but it seems to me that we have at present no sufficient evidence to enable us to discuss it. It is that the Earth, and the planets generally, may exercise an attractive influence on the solar stream-lines.

The difficulty of the apparent indifference shown by certain sets of disturbances to the change in the latitude of the Sun's center,

is not so serious as it might appear. It is only some sequences which show it, and it probably is apparent only, being due to the very marked sympathy between the two hemispheres of the Sun. The formation of a large spot in a given longitude in one hemisphere is not infrequently answered by the formation of a second in the same longitude, but in the other hemisphere, so that we should rather expect some instances of this character than be surprised when they occur. While the tendency of disturbances to recur when the same meridian is on the center of the disk at the end of a year certainly looks as if some at least of the stream-lines only encountered the Earth at a precise node.

INQUIRIES SUGGESTED

The first point brought out by this new view of the solar relation to our magnetic disturbances is the absolute necessity of comparing together the actual traces obtained at magnetic observatories, widely separated from each other, and, in particular, observatories placed on different sides of the equator. The first is necessary that we may be able to distinguish between those disturbances which are truly cosmical and those which are telluric. When the latter are eliminated, a comparison of the records from observatories with opposed seasons should enable us to decide whether the annual inequality, observable in the number and intensity of disturbances, is due solely to the march of the seasons, or to the position of the Sun's equator; or, as the disturbances registered at Greenwich seem to me to suggest, to a combination of both causes.

But apart from the necessity of distinguishing between the disturbances of cosmical and those of telluric origin, the comparison of the intimate details of the traces from observatories differing widely in longitude, ought to be undertaken. A solar streamline, overtaking the Earth, will necessarily strike it first on the sunset arc, and will pass across the hemisphere in daylight; the advancing edge of the stream taking just half a minute to pass from the sunset arc to the arc of sunrise. We might expect that there would be some perceptible difference between the behavior of the magnets in the hemisphere in light, upon which the impact

of the stream is direct and immediate, and that of those in the hemisphere in darkness, which would receive their disturbing currents, as it were, at second hand, since they would be protected from the actual impact of the solar particles; or, in other words, that there would be some difference in the character of a disturbance, depending on the local time at the observing station.

The suggestion made above, that the solar stream-lines must strike the Earth first on the sunset side, raises a point to be determined by the observation of auroræ. These are necessarily seen only in the hemisphere in darkness, but it is conceivable that the general character and progress of the phenomenon, as seen from any given station, may depend upon the position of the Earth at the moment when the stream from the Sun first strikes the Earth; that is to say, when the magnetic disturbance has its first sharp beginning.

Seeing that our magnetic disturbances are due to a solar action, taking place along definite lines, some of which strike the Earth, and some of which do not, the question at once arises: What would happen if one of these streams should just graze the Earth? Would the effect be the same as if it struck it centrally, or would there be a marked difference between the character of the disturbance as registered at a station within the region actually struck by the stream, and as registered at one at a very great distance from that region? More important still: What will happen if one of these streams should fail to strike the Earth at all, but should pass near it either to the north or the south? Will it produce no effect at all, or is it possible that it may give rise to an induced current? In the latter case may it be that the characteristic sharp twitch, instantaneous over the whole Earth, so typical of the more violent storms, denotes that a stream-line has come into actual collision with the Earth, while the more gradual, sluggish, and less-defined disturbances represent the effect of the passage of one of these streams either above or below the Earth without actually encountering it? Clearly, if this conception be admissible, it will do something to remove some of the difficulties suggested earlier. The number of streams actually striking the Earth may be very much smaller than the number of observed disturbances, seeing that many of them may

be due to such near approaches. It renders less serious the difficulty arising from the altered latitude of the center of the disk at the successive returns of a disturbance. We may, in fact, not regard the Earth merely as a globe 8″.8 in radius, for it may be sensitive to streams passing within an undefined distance from it, and thus the effective "catchment area" may be several times as great as the apparent disk of the Earth viewed from the Sun.

If the magnetic disturbances are due to these streams of repelled particles, what is the cause of the cyclical inequality in the diurnal range? Nothing is clearer than that it varies in general sympathy with the spot-activity of the Sun. We should naturally, therefore, expect to find it due to a cause of the same general character as that giving rise to the disturbances. Yet this cyclical inequality is of about the same magnitude as, and is similar in character to, the annual inequality; the diurnal range being greatest in the years of the eleven-year cycle when there are most sun-spots, just as it is also greatest in the months of summer. This would lead us to expect that the annual inequality may not differ in essence from the cyclical, and that both may conceivably be due to the influence of great numbers of very attenuated, feeble, sparse streams, thrown off by the Sun at all times and in many directions, though most abundantly at sun-spot maximum—streams which might individually bear about the same relation to the great rod-like rays seen in the Indian eclipse, or to the stream causing the storm of November 1882, as the minute pores of the Sun's surface, which alternate everywhere with the photospheric granules, do to some gigantic spot, fifty thousand miles in diameter. The varying presentation of different regions of the Earth toward the Sun at different times of the year, involving a greater or less exposure to this influence, would be the cause of the annual inequality, while the varying presentation during the Earth's daily rotation on its axis would account for the diurnal range itself.

Are the particles reaching us from the Sun all of the same size, or, what comes to the same thing, do they all travel with the same rapidity? It is scarcely conceivable that such should be the case. But if not, then it would follow that a great storm would tend to reach us in a succession of disturbances. If it arose from a region

marked by a great spot, that spot would appear to occupy different positions on the disk at the commencement of the different sections of the disturbance; and if it were possible to look down upon the solar system from above, and to detect these streams, instead of a single ray coming from one of these areas of disturbance, we should see a fan-shaped cluster of them, just as we have tails of different types diverging from the heads of comets. It is possible that the explanation of the successive arches, arch above arch, which have been seen in the synclinal structures of the corona, are actual evidence of such different rates of motion, and the careful measurement of the intervals between successive outbursts of activity in the course of a given storm might furnish us with the means of determining the relative speeds with which the particles repelled from the Sun have traveled to us. One consequence, however, should follow: the plane of the fan should lie either in the plane of the Sun's equator, or be parallel to it, so that at the beginning of June and the beginning of December, when the Sun's equator is most inclined to the ecliptic, there would be the greatest tendency for some members of the fan to miss the Earth. At the beginning of March and the beginning of September there would be the greatest tendency, if one member of the fan struck the Earth, for all to do so. In short, disturbances would show a strong tendency, on the average, to be most prolonged just before our equinoxes, and to be shortest just before our solstices. That there are more disturbed days at our equinoxes than at our solstices is a relation to which Mr. W. Ellis has already drawn attention, and perhaps this is where we may find its explanation.

APPENDIX

As an example of the kind of evidence offered by the magnetic disturbances recorded at Greenwich of the influence of the synodic rotation period of the Sun upon them, I give here the sets of disturbances drawn from those which I have catalogued for the years 1895 to 1898. The letters G, V, A, M, in the second column signify "great," "very active," "active," and "moderate;" a "great" disturbance being one in which the maximum amplitude of movement in declination exceeds 60′; a "very active," in which it exceeds 40′; an "active," 30′; and a "moderate," 20.′ The same numeration of the rotations, the same prime meridian and the same sidereal rotation period (25.38 days) have been adopted as in the "Heliographic Results" given in the annual volumes of the *Greenwich Observations*.

Reference Number of Disturbance	Class	Time of Commencement	Number of Rotation	Longitude of Sun's Center	Latitude of Sun's Center
196	M	1895 Feb. 8d 13h	553	234°.0	−6°.6
197	A	9 11	...	222.0	−6.7
199	A	Mar. 8 14	554	224.7	−7.3
203	M	May 29 3	557	228.0	−0.9
205	A	Oct. 12 16	562	222.8	+6.0
206	A	Nov. 9 13	563	215.2	+3.3
207	A	1896 Jan. 3 0	565	217.7	−3.5
208	M	31 12	566	202.4	−6.1
210	V	Feb. 28 9	567	195.4	−7.2
212	M	Mar. 26 13	568	197.2	−6.7
214	A	1896 May 17 12	570	230.9	−2.1
215	M	July 11 15	572	221.3	+4.2
218	M	Aug. 6 16	573	236.8	+6.3
234	V	1897 Dec. 11 3	591	230.8	−0.7
245	G	1898 Sept. 9 14	601	233.6	+7.2
198	M	1895 Feb. 15 14	553	141.3	−6.9
201	A	Apr. 11 6	555	140.7	−5.8
209	A	1896 Feb. 4 12	566	149.7	−6.4
213	V	1896 May 2 13	569	68.6	−3.8
216	M	July 23 18	572	60.9	+5.3
217	A	1896 Aug. 1 12	573	305.2	+6.0
219	M	29 17	574	292.6	+7.2
222	A	1896 Oct. 11 13	575	86.9	+6.0
223	A	Nov. 7 12	576	91.5	+3.4
224	V	Dec. 3 17	577	105.9	+0.3
225	A	1897 Jan. 2 12	578	73.5	−3.5
226	M	Feb. 25 15	580	80.8	−7.2
229	A	Apr. 20 12	582	90.3	−5.0
230	M	1897 Apr. 23 13	582	50.1	−4.7
231	M	May 20 21	583	48.7	−1.8
232	M	1897 Sept. 4 13	587	77.7	+7.3
233	M	Oct. 1 20	588	77.5	+6.6
235	V	1897 Dec. 20 13	591	106.6	−1.9
236	M	1898 Jan. 16 16	592	109.4	−4.9
238	M	Feb. 12 14	593	115.0	−6.8
240	M	Mar. 11 14	594	119.8	−7.2
239	M	1898 Feb. 14 13	593	89.2	−6.9
241	G	Mar. 15 1	594	73.9	−7.1
242	M	Apr. 12 16	595	56.2	−5.7
246	A	1898 Oct. 25 12	603	347.8	+4.8
247	M	Nov. 21 12	604	351.8	+1.9

Out of the fifty-two disturbances catalogued in these four years no fewer than forty-one fall into one or other of the above sets.

86 Tyrwhitt Road,
St. John's, London, S. E.,
December 12, 1904.

THE EFFECT OF CAPACITY AND SELF-INDUCTION UPON WAVE-LENGTH IN THE SPARK SPECTRUM

By GEORGE W. MIDDLEKAUFF

INTRODUCTION

In line of sight work the comparison spectrum is usually that of the spark. For this reason it is a matter of importance to know whether or not the wave-lengths of the spark spectrum remain constant under varying external conditions of capacity, self-induction, etc. Although considerable work has been done on this subject during the last few years, there is still such a diversity of opinion among the observers that the question cannot be considered as settled. In view of this fact, Professor Ames suggested to the writer that an investigation along this line, with the facilities offered in the physical laboratory of the Johns Hopkins University, would be of interest. Accordingly this work was carried out in the spring of 1903.

The iron spectrum was selected as the subject of study, and the work was undertaken with two principal objects in view, namely, (1) to produce the spectrum under the greatest possible variations in capacity and self-induction, and find the effect, if any, upon the wave-lengths of the lines; and (2), to make accurate measurement of the lines in the spark spectrum throughout the region utilized by line of sight observers.

EFFECT OF CAPACITY AND SELF-INDUCTION UPON WAVE-LENGTH

Historical review.—Exner and Haschek,[1] in the course of their measurements of the ultra-violet spark spectra of the elements, observed that in many instances the wave-lengths of lines in the spark spectrum differed considerably from the wave-lengths of the corresponding lines in the arc, the difference being often as much as 0.3 of an Ångström unit. This difference they considered as being due to pressure in the spark, and with data taken from the tables of Humphreys and Mohler[2] they estimated the pressure in the spark to be from 24 to 30 atmospheres.

[1] *Sitzungsberichte der Kais. Akad. der Wiss. in Wien*, 1897 *et seq.*

[2] *Astrophysical Journal*, 1896 and 1897.

Then Haschek and Mache[1] undertook to measure this assumed pressure by placing the spark in an air-tight vessel filled with air and furnished with a manometer. On discharging the spark they observed a sudden rise in the manometer, and interpreted it as a manifestation of a pressure in the spark. However, the value they thus obtained was far greater than the value of the pressure calculated from the difference in wave-length between arc and spark lines. They further found[2] that as they increased the amount of capacity across the discharge circuit the effect was increased to a maximum and then decreased. The potential used in the experiment was furnished by a powerful transformer.

Then Mohler[3] with the use of an induction coil and a Rowland grating, found that with an increase of capacity there was an increase in the shift of the lines which seemed to approach a maximum value; but the calculated pressures obtained were by no means as great as those found by Haschek and Mache.

In responding to Mohler's results, Haschek and Mache[4] claim that the former's work is but a confirmation of their own, the difference in value being due to the difference in energy produced by a transformer and an induction coil, respectively.

Contrary to the results of the above observers, Eder and Valenta,[5] on investigating some of the lines in which Exner and Haschek believed they had found an increase in wave-length due to capacity, obtained photographs which indicated no change whatever.

Haschek,[6] from later experiments, concluded that in many instances lines which in the spark were increased in wave-length by equal amounts were increased by unequal amounts in the arc under pressure, and conversely; also that even in the spectrum of the same element the wave-lengths of the lines were increased by unequal amounts, indicating that other influences besides pressure were making themselves felt; and hence the pressure in the spark, if it be a reality, cannot be determined directly from any one line of the spectrum. From the same experiments he concluded, further, that there were increases

[1] *Sitzungsberichte der Kais. Akad. der Wiss. in Wien*, 1898.

[2] *Astrophysical Journal*, **9**, 351, 1899.

[3] *Ibid.*, **10**, 204, 1899.

[4] *Ibid.*, **12**, 50, 1900.

[5] Kayser, *Handbuch der Spectroscopie*, **2**, 308.

[6] *Astrophysical Journal*, **14**, 187, 1901.

in wave-length produced by increasing the amount of luminous vapor in the spark. This, however, is contrary to the results of Humphreys and Mohler,[1] who found that in the case of the arc pressure only and not vapor caused an increase in wave-length of the lines. It is also contrary to the opinion of Kayser,[2] who states that in all his investigations of arc spectra he observed no change in wave-length due to the amount of vapor present in the arc.

Then Kent[3] undertook to verify the results of Haschek, and concluded that in the case of titanium there was a shift due to capacity, but that it did not amount to more than 0.04 of an Ångström unit for lines in which Haschek observed as much as 0.13 of a unit. Later this same observer made an investigation[4] of the possible effect of various circuit conditions upon the wave-length of the lines in the spark spectrum, using titanium as the subject of study. He concluded that there were changes in wave-length produced by changes in capacity, self-induction, resistance in field circuit of alternator, impedance in the primary circuit of the transformer, length of spark-gap, etc. In short, he concluded that almost any variation in the condition of the electric circuit would produce a corresponding change in the wave-length of the lines of the spark spectrum.

THE PRESENT INVESTIGATION

Apparatus.—The grating employed in this investigation was a twenty-one and a half foot concave Rowland grating with 20,000 lines to the inch, mounted as described by Professor Ames in the *Philosophical Magazine*, p. 369, 1889, and being in all respects the same instrument used by Humphreys and Mohler in their work on pressure shift. For the purpose of comparison of spectra, the camera carries a shutter consisting of a long brass plate, capable of revolution around a horizontal axis, and having throughout its length a longitudinal opening of a width equal to the thickness of the brass plate; so that when the shutter is in a vertical position the photographic plate is exposed along a strip extending over the whole length of the plate and over a width equal to the thickness of the shutter. When

[1] *Ibid.*, **3**, 114–137, 1896.

[2] *Handbuch der Spectroscopie*, **2**, 297, 308–310.

[3] *Astrophysical Journal*, **14**, 201, 1901.

[4] *Ibid.*, **17**, 286, 1903.

the shutter is turned horizontal, the central strip is covered, and the remainder of the photographic plate above and below the strip is exposed. To avoid any jarring of the camera when the shutter was turned between comparison spectra, the shutter was detached from the camera and supported by two iron clamp-stands which stood upon the floor. As the beam on which the camera rested was supported by the walls of the building, there could be no possible jarring due to the motion of the shutter. In addition to the shutter already described, there were three other shutters placed a few inches in front of it. These were each about seven inches long, were placed end to end, and were capable of turning about the same horizontal axis. They were also supported by the clamp-stands mentioned above. When all three were in a vertical position, no light from the grating could fall upon the photographic plate. When the left-hand one, say, was in a horizontal position and the other two vertical, only the left end of the plate could be exposed, no matter how the first shutter with the opening in it was turned. With the middle one horizontal and the end ones vertical, only the middle portion of the plate could be exposed, etc. These four shutters were operated by means of cords leading to a point near the slit. This was done so that the operator need not move from a fixed position during the exposure of the plate, and he might thus avoid possible shaking of the apparatus due to his walking over the floor.

The spark was produced by a 50-volt alternating current of about 25 amperes with a frequency of 133 cycles per second. After being stepped up to about 600 volts, it was passed through a transformer, which raised the potential sufficiently to produce a spark about two centimeters in length.

The spark terminals were cylindrical rods of Norway iron, 8 mm in diameter and turned down at the spark ends to the shape of a blunt lead-pencil point. These points would wear down slightly during a long exposure, but care was taken always to turn them to the proper shape before each and every exposure. They were given this shape so that the spark would keep on the slit all the time of exposure, and not jump about as it would with terminals more blunt and flat.

An auxiliary spark-gap was tried in series with the main spark-gap, but as there was no appreciable improvement in the spark, so

far as could be noticed by the eye or ear, no photographs were taken with it in.

The arc for comparison spectra, in the case of plates to be measured for standards, was produced by a 110-volt direct current of about 10 amperes. The arc terminals were also of Norway iron rods, these being about a centimeter in diameter.

Both the arc and spark lamps were placed (the arc nearer the slit) upon a platform which was movable upon two knife-edge ways in a direction parallel to a line drawn through the centers of the slit and grating respectively. Stops were placed before and behind the platform at such a distance from it that when it was against one of them the arc was in focus, and when it was against the other the spark was in focus; that is, in both cases the source of light was in precisely the same place at a distance of 130 cm from the slit.

The light was focused upon the slit by means of a quartz condensing lens, which was never disturbed during the exposure on any one given plate, so that all exposures would have the grating as nearly as possible equally illuminated. The spark-gap was usually 8 or 9 mm in length and its image upon the slit about 6 mm. Care was taken always to have the image as symmetrical as possible with respect to the slit; but in many instances, however, especially with the self-induction in circuit, the image during exposure passed through many unsymmetrical forms.

Immediately back of the slit was a card screen supported by a beam perfectly independent of the mounting of the grating. This screen was movable about a horizontal axis and could be raised or lowered from the slit without disturbing the rest of the apparatus.

The capacity consisted of plates of copper foil and glass, all surrounded with paraffin, and could be varied from 0.0085 to 0.0739 of a microfarad. The self-induction apparatus consisted of three coils of No. 10 copper wire, and the amount of induction could be varied from about 0.00007 to 0.0012 of a henry. The whole of the induction, or any part of it, could be thrown in or out of circuit without stopping the spark.

The plates used were Seed's No. 27 and Cramer's Isochromatic, all cut to 1¼ by 19 inches, and were carefully developed with a hydrochinon solution according to Jewell's formula.[1]

[1] *Astrophysical Journal*, 11, 240, 1900.

The true photographic focus of the grating was carefully determined by empirical settings, and the time of exposure varied from 15 to 60 seconds for the arc, 3 to 10 minutes for the spark without self-induction, and from 10 to 60 minutes for the spark with self-induction.

All measurements on plates were made with the dividing engine which is fully described by Humphreys in the *Astrophysical Journal*, **6**, 180, 1897, and also by the method described at the same place.

Method of exposure.—So far as known to the writer, all observers on the shift of spark lines have used an arc spectrum for comparison, and have photographed the two spectra on the same plate. This, of course, necessitated the change of light-source and the possibility of error due to the two sources not being in turn at exactly the same point.

To avoid error from this source, the method adopted in the present investigation was to compare the spectra of the *same* spark under any two given external conditions. Since the capacity and self-induction could be thrown in or out by means of switches, the spark was kept going from the beginning to the end of all exposing on any one plate.

The general plan of exposure will be understood from the following example. Suppose the plate is to be taken to study the effect of self-induction. The spark is first tried with and without self-induction in series to find out whether the image falls on the slit and whether the grating is properly illuminated in both instances. Having made any necessary adjustments, the self-induction is thrown out, and the shutter at the slit is turned down to keep the light from the spark off the grating until the photographic plate is adjusted in the camera. With the camera shutter, *A*, vertical and the other three, *B*, *C*, *D*, horizontal, the plate is ready to be exposed over the strip *ab* along its whole length. The shutter at the slit is now raised and the exposure begun. When the proper time for the exposure has expired, the shutters *C*, *D*, and *A* are turned in the order named, so that now the portions 1 and 2 of only the end section of the plate are exposed. When these are exposed as long as *ab* was, *B* is turned up and the self-induction is thrown in circuit; after which the shutter, *C*, is let down to expose the portions 3 and 4. This exposure being finished, *C* is turned up, the self-induction is thrown out, and

the shutter D is let down, thus exposing 5 and 6 under external conditions identical with those under which the middle strip ab and the sections 1 and 2 were exposed. Hence if no mechanical shift occurred during the exposure, the lines in 1 and 2, and 5 and 6, will be exactly in line with the corresponding lines in the section ab. Or, if the apparatus was disturbed during the exposure of 3 and 4, causing the lines in them to be shifted, the lines in 5 and 6 will be shifted an equal amount. If, however, the lines in both the end sections are perfectly in line with those in the strip ab, and those in 3 and 4 are not, we can be sure that the difference is a *true* shift.

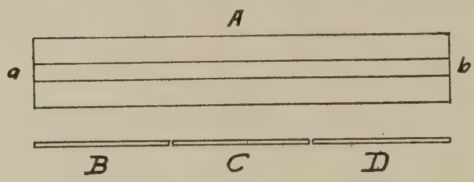


Fig 1

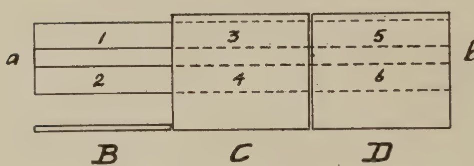


Fig. 2

Results.—A large number of plates were taken by the method described above, to test for a shift due to self-induction; and it was invariably found that, so far as the accuracy of measurement permitted, no shift ever occurred when the self-induction was thrown in circuit. The self-induction spectrum was always photographed in C the middle section, sometimes outside, at other times inside. The order in which the sections were taken was also varied, but in every case the self-induction spectrum was checked before and after its exposure by a spectrum without self-induction and with the capacity the same.

A number of plates were also taken to compare the spectra of the spark with large and small capacities, the variations being made from 0.0085 to 0.0739 of a microfarad. In these the lines were, of course, quite broad; but within the limits of accuracy of the measurements no sensible change in the position of the lines was observed.

In the measurement of the lines on all these plates, great care was taken to make the settings, not on the middle of such lines as were unsymmetrically broadened, but on the most intense portion, or center of gravity. For the purpose of measurement, the most

useful plates were those of short exposure, because on them the broadened and diffused portions of the lines were the least extended.

A number of plates were also taken of the titanium spectrum in the region observed by Kent. The same variations were made in capacity and self-induction as in the case of iron; but, as before, the shift, if any, was too small to be detected.

Hence the conclusion to be drawn from the present research is that in the case of a spark discharge in air at atmospheric pressure, there is no change produced in wave-length by variations of capacity or self-induction within the range specified.

A further conclusion, which has been reached from a careful examination by the microscope of all the many photographs taken with the arc and spark spectra on the same plate, is that so far as can thus be determined, there is no appreciable difference in wave-length between the same lines as observed in the arc and spark spectra.

Since the completion of this investigation, Eder and Valenta[1] have published the results of an attempt to verify the conclusions of Haschek in regard to the effect upon wave-length of the amount of luminous vapor present in the spark. In their experimental arrangements they followed strictly those conditions under which Haschek believed he found shifts. They employed powerful induction coils with a sparking distance of from 12 to 25 cm and correspondingly large condensers across the discharge circuit. Even with such extreme conditions, they came to the following conclusions: "(1) no displacements of measurable magnitude occur in the spark spectrum of zinc as compared with the lines of the arc; (2) the quantity of the element present, or the partial pressure of its vapor, produces no displacement of the lines of the spark spectrum."

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[1] *Sitzungsberichte der k. Akad. der Wiss. in Wien,* **112,** II*a*. Communicated October 22, 1903. Translation, *Astrophysical Journal,* **19,** 251, 1904.

A STUDY OF THE CONDITIONS FOR SOLAR RESEARCH AT MOUNT WILSON, CALIFORNIA[1]

BY GEORGE E. HALE

In 1902, Dr. S. P. Langley addressed a communication to the Carnegie Institution recommending the establishment of an observatory at a very high altitude for the special purpose of measuring the solar radiation. In this communication Dr. Langley offered reasons for his belief that the solar radiation may undergo changes of intensity corresponding with those great changes of solar activity which are so strikingly illustrated in the sun-spot cycle. This communication was referred to an advisory committee appointed by the Carnegie Institution to report on various astronomical projects which had been submitted. The committee consisted of Professor E. C. Pickering, chairman; Professor Lewis Boss, Dr. S. P. Langley, Professor Simon Newcomb, and the writer. In its report to the Carnegie Institution, the committee expressed its approval of Dr. Langley's proposal and recommended, in case the Institution felt inclined to pursue the matter further, that a special committee be appointed to make a detailed report on the requirements of a complete solar observatory. It was also recommended that a project for an observatory in the southern hemisphere be investigated and reported upon by the same committee.

As a result of this recommendation, a committee, consisting of Professor Lewis Boss, chairman; Professor W. W. Campbell, and the writer, was appointed in December 1902 to report upon the proposed southern and solar observatories. The report of this committee may be found in *Year Book* No. 2 of the Carnegie Institution. This report also includes a detailed account by Professor W. J. Hussey of his telescopic tests of atmospheric conditions at sites in southern California and Arizona, where he had been sent by the committee. Professor Hussey strongly recommended, as the result of his tests, that Mount Wilson, near Pasadena, Cal., be chosen as the site of the proposed solar observatory, in case the Carnegie Institution decided to establish it.

[1] *Year Book No. 3 of the Carnegie Institution of Washington.*

My first visit to Mount Wilson was made in company with Professor Campbell in June 1903. Professor Hussey had practically completed his tests and desired that we should see for ourselves the conditions he had found. Previous observations of the Sun at Pike's Peak, Mount Etna, and Mount Hamilton had in no wise prepared me for my experience on Mount Wilson. On certain occasions, it is true, I had seen the solar image sharply defined on Mount Etna in the very early morning hours. On Mount Hamilton, also, the solar image is sometimes good; but the testimony of those who have observed the Sun there was decidedly unfavorable. It was therefore with intense satisfaction that on each of the four days of my stay on Mount Wilson I found the definition of the solar image almost perfect, to be rated at from 8 to 9 on a scale of 10.

This visit was necessarily a hurried one, and it was evident that before Mount Wilson could be determined upon as the best available site for an observatory, observations extending over a long period of time would be necessary. As circumstances required that my family should spend the winter of 1903–4 in southern California, I decided to take this opportunity to make a more complete test of atmospheric conditions on Mount Wilson. Before arrangements had been made for living upon the mountain, I made frequent trips from Pasadena to Mount Wilson during the months of December, January, and February, observing the Sun on each occasion with a telescope of $3\frac{1}{4}$ inches aperture, and noting the prevailing weather conditions. The extraordinary absence of wind, which had seemed so characteristic a feature of the mountain during Professor Hussey's visit, could not be said to continue throughout the winter months. High gales sometimes occur at this season, and the average wind velocity is greater than during the summer. Nevertheless, the wind during the day was usually very light, and on many occasions the quiet days of the previous June seemed to be almost exactly duplicated, except that the temperature was lower. For weeks together not a cloud would be seen in the sky, and the summer serenity was in some measure retained until well into January. Later it was broken by storms, but these practically ended with April.

As the solar definition proved to be surprisingly good for this season of the year, I was soon convinced that Mount Wilson offered

exceptional opportunities for both solar and stellar work and that a systematic test of conditions should be inaugurated at the earliest possible moment. Accordingly, I commenced on March 1 to render habitable an old log cabin on the mountain that had been in a state of partial ruin for many years. The cabin, known locally as the "Casino," became our headquarters, where we have lived throughout our work on Mount Wilson. Tests of the solar definition were made as often as possible with the telescope already mentioned, and on April 15 several meteorological instruments provided by the Carnegie Institution were installed. Since that time, with only such interruptions as have been made necessary by the enforced absence of the observers, the instruments have been read at stated hours by Mr. Ferdinand Ellerman or Mr. W. S. Adams, who have also made regular tests of the seeing with the telescope mentioned above.

Through important financial assistance rendered by Mr. Arthur Orr, of Evanston, Ill., and Mr. John D. Hooker, of Los Angeles, and the exceptional facilities kindly granted by the Atchison, Topeka & Santa Fé Railway Co., through President Ripley, it became possible to bring from the Yerkes Observatory the small cœlostat which had previously been sent to the eclipses of 1900 (North Carolina) and 1901 (Sumatra). It had been my purpose to bring out the Snow telescope, but lack of sufficient funds prevented me from doing so. The smaller cœlostat was accordingly erected on the mountain, where it yielded excellent photographs of the Sun, amply sufficient to give objective evidence of the high quality of the observational conditions.

During my first visit to Mount Wilson the only unfavorable feature was the presence of fine dust in the air, which was conspicuous not only in the valley below, but also seemed to extend to a considerable altitude above the mountain. This was by no means sufficient to affect greatly the transparency of the sky, except very near the horizon. Nevertheless, the Milky Way did not stand out with the degree of contrast which one expects to see in a very transparent atmosphere. On my return trip to Chicago through the San Gabriel Valley the dust seemed so conspicuous that I feared it might prove an important objection to Mount Wilson as a site for an observatory. In most classes of solar observation dust does not play a very important part, and the great steadiness of the image would far outweigh any objec-

tions which might result from this cause. But in other classes of work which were contemplated for the proposed observatory, this dust, if persistent, would inevitably prove a serious obstacle. For example, in determinations of the value of the solar constant and in the photography of faint nebulæ, the absorption and scattering of light produced by dust in the atmosphere may interfere greatly with the work. It accordingly seemed that special attention should be given to the question of dust in the atmosphere above Mount Wilson. It has fortunately turned out, as will be shown later, that the presence of any appreciable amount of dust in the air above the mountain is so exceptional a phenomenon as to constitute no important objection to Mount Wilson as an observatory site.

After a brief statement regarding the conditions found at Mount Wilson had been presented to the Executive Committee of the Carnegie Institution, in April 1904, they decided to make a grant of a sum sufficient to provide for the erection and use of the Snow telescope on the mountain. The Yerkes Observatory loaned the telescope, and the University of Chicago provided the salaries of some of the observers. The work accomplished on the mountain since this grant was made has been sufficient to serve as a reliable basis for estimates on the cost of a large solar observatory, besides giving valuable experience regarding the necessary methods and cost of construction under the unusual conditions existing at the summit of a mountain nearly 6,000 feet in height. In view of their bearing on the question of a solar observatory, I have accordingly included in my report some remarks on the principal obstacles encountered and overcome in the construction of buildings and the transportation of instruments and materials.

REQUIREMENTS OF A SITE FOR A SOLAR OBSERVATORY

It is desirable to recapitulate here the purposes and plans for a solar observatory which were given at some length in *Year Book* No. 2 of the Carnegie Institution. At the outset, it should be stated that the term "solar observatory" is used here in a broad sense, since it is not intended to exclude from the program certain investigations of stars which are of fundamental importance in any general study of the problem of stellar evolution. For the Sun is a star, comparable in almost every respect with many other stars in the heavens, and

rendering possible, through an intimate knowledge of its own phenomena, the solution of some of the most puzzling questions in the general problem of stellar evolution. Conversely, however, the stars are suns, and if we would know the past and future conditions of the Sun, we must examine into the physical condition of stars which represent earlier and later stages of development. It will be seen that there is ample ground for the inclusion in the equipment of a solar observatory of certain instruments especially designed for the study of stellar problems.

The plan of work proposed for the observatory, as outlined in *Year Book* No. 2, includes the following classes of observations:

1. Frequent measurements of the heat radiation of the Sun, to determine whether there may be changes during the sun-spot cycle in the amount of heat received from the Sun by the Earth and in the relative radiation of the various portions of the solar surface.

2. Studies of various solar phenomena, particularly through the use of powerful spectroscopes and spectroheliographs.

3. Photographic and spectroscopic investigations of the stars and nebulæ with a very powerful reflecting telescope, for the principal purpose of throwing light on the problem of stellar evolution.

The present opportunity for important advances in these three departments of research is very unusual. Since the publication of *Year Book* No. 2, Dr. Langley has offered reasons to believe that an actual change in the amount of heat emitted by the Sun occurred in March 1903. It is hardly necessary to say that a change in the intensity of the Sun's heat, if actually established, might have a most important bearing upon many questions relating to the Earth, and, at the same time, be of capital interest in its relationship to the problem of the solar constitution. Through the force of circumstances, Dr. Langley's observations have been made under the very unfavorable conditions which obtain at Washington. If they could be continued at a considerable altitude, at a point above the denser and more fluctuating region of the Earth's atmosphere, the question as to what changes actually occur in the solar radiation could doubtless be answered in a thoroughly satisfactory manner.

In the study of the phenomena of the Sun's surface and atmosphere we again enter a remarkably fruitful field of research. Within the

past few years the instruments available for work in this field have been greatly developed, and now only await application on a large scale in order to secure a great number of new results which have hitherto been entirely out of reach. But even if the means were available for supplying the necessary instruments to existing observatories, they could not be successfully employed without atmospheric conditions much superior to those at present available. In work of this nature, success depends upon the perfect definition of the solar image and the absence of those disturbances from which the amosphere at existing observatories is almost never free. For this work, therefore, an elevated station in a region of great atmospheric calm is absolutely essential. Furthermore, the site must be free from the disturbing factors which frequently prevent good observations from being obtained on mountain summits.

In the third class of investigations required to complete the program of a properly equipped solar observatory, similar possibilities of advance exist. Within the past few years the remarkable advantages of the reflecting telescope have been demonstrated. It now only remains to construct a large and powerful instrument of the type shown by these experiments to promise success. With such an instrument, immense new fields of investigation of the highest importance in their bearing on the problem of stellar evolution could be immediately occupied. Here again, however, the unfavorable atmospheric conditions at almost all existing observatories would render the construction of a large telescope almost useless. To be successful, such an instrument must be erected at a site where the night-seeing is nearly perfect, the sky clear and transparent, and the average wind velocity very low. Under such conditions, a properly constructed telescope of large aperture would undoubtedly yield results greatly surpassing those hitherto obtained.

These considerations are sufficient to define the general character of a site suitable for a well-equipped solar observatory. There are other points, however, which must be taken into account. A solar observatory provided with an outfit of instruments, and then left to do its work without the possibility of improvement or change, could never attain the best results. On the contrary, it must have the means of producing new types of instruments and modifying old ones, as

the development of the work may suggest. In other words, a shop completely equipped with all appliances necessary for the most refined construction of both the mechanical and optical parts of instruments should form an integral part of a solar observatory. A shop of this kind cannot be conducted without great difficulty and expense, if far removed from large cities and other sources of supply. This is only one of many reasons which would render it desirable to select an observatory site within easy reach of the facilities afforded by a large city.

In his recommendation for the establishment of an observatory for the purpose of determining whether the heat radiation of the Sun undergoes change, Dr. Langley pointed out the desirabliity of making the observations at a height of some 20,000 feet above sea-level. Apart from the excessive difficulty and expense of conducting an observatory at such an elevation, which are best appreciated by those who have worked at great altitudes, the inaccessibility of high mountain peaks would stand in the way of such an undertaking. But it nevertheless might have been carried out, at a somewhat lower altitude, if the recent development of Dr. Langley's work at Washington had not indicated that the great mass of observations could undoubtedly be made to good advantage at a much lower station. The increasing perfection of the observational method has, indeed, permitted fairly good results to be obtained under the very unfavorable conditions which exist at Washington. Nevertheless, it by no means follows that Dr. Langley's purpose could be accomplished at such a point. The humidity of our atmosphere is a most serious obstacle in this particular work, since the solar heat is very subject to absorption by water vapor. It is therefore desirable to establish the instruments a least a mile above the dense and disturbed layers of the atmosphere which lie near the sea-level. Certain problems connected with the investigation may render it desirable to make some of the observations at a higher altitude, reaching from 12,000 to 15,000 feet. We conclude, therefore, that the principal work should be done at a station having an elevation of 5,000 to 6,000 feet, in a dry climate, where the weather is continuously clear over long periods of time. The work at higher altitudes, if needed at all, could in all probability be completed in two or three summers by expeditions equipped with

a portable outfit erected at an altitude of from 12,000 to 15,000 feet. It would thus be convenient to have the principal station at a lower altitude, not far removed from accessible mountains of this considerable elevation. It would be inadvisable, for reasons which it is hardly necessary to specify, to establish the principal station at an altitude much greater than 6,000 feet.

POSITION AND NATURAL RESOURCES OF MOUNT WILSON

From a meteorological standpoint, the state of California may naturally be divided into three parts. In the northern region the rainfall is very considerable, much cloudiness prevails, and in almost all respects the conditions are very unfavorable for astronomical work. The central region, which may be considered to extend as far south as Point Concepcion, is favored with much better weather conditions, best exemplified at the Lick Observatory, on Mount Hamilton, where a high average of night-seeing is maintained during a large part of the year. Except for the frequent winds at night, which interfere with some classes of work, Mount Hamilton might be regarded as an almost ideal observatory site, at least for night observations. For solar work it may not be superior to certain stations in the eastern part of the United States, because of the excessive radiation from the heated slopes of the mountain, which is almost devoid of trees near the summit.

In the southern part of California the climatic conditions are decidedly different from those which prevail in the two other sections of the state. The much lighter rainfall is naturally associated with fewer clouds, a remarkably steady barometer, and very light winds. During a part of the year the fog rolls in from the ocean and covers much of the San Gabriel Valley during the night. But these fog-clouds rarely attain elevations exceeding 3000 feet, except when storm conditions prevail during the winter months. The mountains of the Sierra Madre range rise high above the fog, and during a great proportion of the year they enjoy practically continuous sunshine. During the summer months the sea breeze blows for a large part of the day, but it attains only a low velocity, which decreases in passing from the valley to the mountain tops and in going inward from the coast.

Mount Wilson is one of many mountains that form the southern boundary of the Sierra Madre range. Standing at a distance of thirty miles from the ocean, it rises abruptly from the valley floor, flanked only by a few spurs of lesser elevation, of which Mount Harvard is the highest. Except for a narrow saddle, Mount Wilson is separated from Mount Harvard by a deep cañon, the walls of which are very precipitous. Farther to the west, beyond the saddle leading to Mount Harvard, the ridge of Mount Wilson forms the upper extremity of Eaton Cañon, which leads directly to the San Gabriel Valley. East and north of Mount Wilson lies the deep cañon through which flows the west fork of the San Gabriel River, and beyond this rises a constant succession of mountains, most of them higher than Mount Wilson, which extend in a broken mass to the Mojave Desert. The Sierra Madre range forms the northern boundary of the San Gabriel Valley, which is further protected toward the east from the desert by the high peaks of the San Bernardino range. Through the Cajon Pass, where the Atchison, Topeka & Santa Fé Railroad enters the valley, winds from the desert frequently blow, bringing vast quantities of dust, which sometimes diffuses through the lower air over the entire valley. This dust but rarely reaches an elevation as great as that of Mount Wilson, though I have seen a few windstorms that carried the dust of the desert directly over the Sierra Madre range and into the valley below.

For the most part, the readily accessible mountains on the southern boundary of the Sierra Madre range have few trees near the summit, and enjoy but small supplies of water. Mount Wilson is remarkable in having a fine growth of trees covering its summit, and in possessing within easy reach of its highest point several large springs of water, which afford a good supply even during very dry seasons.

In a dry country the question of a pure and permanent supply of water is of paramount importance. It is therefore desirable to give more definite information of the springs near the summit of Mount Wilson. Some of these are located at Strain's Camp, where, for many years, they have supplied the necessities of summer visitors, who frequently occupy tents here for considerable periods of time. Two wells have been dug at Strain's Camp, and these are regarded as excellent sources of pure water.

In accordance with the terms of the lease of the property at present occupied as an observatory site on Mount Wilson, the water rights on the mountain are to be equally divided between the owners of the property and the occupants of the observatory site. It seems probable that the wells at Strain's Camp, if properly developed, would supply the purposes of a large observatory. If not, more water could easily be developed on the mountain; it may appear desirable to obtain water from a stream in one of the neighboring cañons, about 1000 feet below. The expense of pumping to this height would be great, and the stream can be relied upon as a never-failing source of water. A water-tunnel on the south face of the mountain has been reserved by the owners of the property for the purpose of supplying Martin's Camp, and is not included in the equal division of the remaining water rights. A method of securing more water, which could undoubtedly be employed with advantage, would be through the use of large storage tanks, in which water could be collected during the rainy season, either by pumping from the overflowing wells or by catching the rain as it falls on roofs or other large surfaces provided for the purpose.

TRANSPORTATION AND CONSTRUCTION

Much granite is available on Mount Wilson for the purpose of construction, but in the portion of the mountain selected for the observatory site it is not so easily obtained as might be wished. This is due to the fact that much of the granite is decomposed, and consequently too soft for building purposes. The hard and the decomposed granites occur together, so that if a quarry is started at a point where plenty of hard granite seems to be present, it sometimes happens that the supply is soon exhausted, leaving only decomposed granite below. Men experienced in matters of this kind have been quite unable to judge whether selected spots could be relied upon to furnish a good supply of hard granite. This fact greatly increases the expense of constructing stone piers, since quarries may have to be abandoned after having been opened at considerable cost. However, some abundant sources of excellent stone can be rendered easily accessible by the extension of roads constructed for work now in progress.

Numerous fallen trees on Mount Wilson, which are not yet greatly decayed, will furnish an abundant supply of firewood for many years to come. They cannot be depended upon, however, to yield any wood for building purposes, and as the living trees may not be destroyed, all lumber must be taken to the summit of the mountain from Pasadena. This raises the question of transportation over the mountain trail—a matter of vital importance in constructing an observatory. The "Toll Road" or "New Trail," which extends from the summit of the mountain to the foot of Eaton Cañon, is well adapted for all ordinary packing with animals, though it is much too narrow to permit wagons to pass over it. At present, all except the heaviest articles are taken to the summit of the mountain by means of burros and pack-mules, each of which can carry a load ranging from 80 to 200 pounds. It is evident that transportation of building materials by this means must be very slow and expensive, since the trail is nine miles in length to the foot of Eaton Cañon, six and one-half miles distant by road from Pasadena. But, as compared with most mountains, Mount Wilson is unusually accessible from cities, Pasadena being so close at hand, and Los Angeles, with its large sources of supply, being only nine miles farther away.

For transporting heavy castings and other similar articles, we have found it necessary to construct a special four-wheel carriage, two feet in width. On this loads of a thousand pounds have been taken to the summit without difficulty. By widening the trail to six feet, the heaviest castings required for a solar observatory probably could be transported.

WEATHER

So far as cloudiness is concerned, the records of the Weather Bureau at Los Angeles are of comparatively little value for our present purposes. The fog rolls in from the ocean night after night, and sometimes hangs over Los Angeles throughout the day during the winter season. But Mount Wilson reaches far above this layer of clouds, and thus frequently enjoys sunshine when the valley below is completely covered. Our daily percentage record of cloudiness, beginning on April 18, 1904, may be found in the following table. A dash signifies that no observation was made.

There were many days which were cloudy at the time of observation, but nevertheless suitable at other hours for solar work. Adding these to the record, it may be said that the actual number of days on

CLOUDINESS

Day of Month	April		May		June		July		August	
	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.
1........	...	...	100	20	75	75	0	0	0	0
2........	...	...	0	5	5	0	0	0	0	0
3........	...	...	0	0	0	0	0	0	90	10
4........	...	...	0	0	0	0	0	0	5	25
5........	...	...	0	0	0	0	0	0	0	0
6........	...	...	0	0	0	0	0	0	30	100
7........	...	...	0	0	0	0	0	—	40	60
8........	...	...	0	0	0	0	0	10	50	40
9........	...	...	70	85	0	0	0	—	0	0
10........	...	...	5	5	0	0	—	—	0	0
11........	...	...	0	0	0	0	0	0	0	0
12........	...	...	0	0	0	0	0	0	30	50
13........	...	...	0	0	0	0	0	0	20	20
14........	...	...	0	0	0	0	0	0	80	80
15........	...	...	0	0	0	25	0	0	0	0
16........	...	...	0	0	5	0	0	—	0	5
17........	..	...	0	0	0	0	—	—	0	0
18........	...	...	0	0	0	10	—	0	10	5
19........	100	100	0	0	0	0	0	0	0	0
20........	50	5	0	75	0	0	5	5	0	0
21........	0	0	25	5	0	0	—	50	0	5
22........	70	100	0	50	0	0	45	5	75	80
23........	0	0	5	5	0	0	35	5	20	30
24........	0	5	0	0	0	0	5	10	60	5
25........	75	0	100	100	0	0	35	15	5	5
26........	100	100	100	0	0	0	20	15	5	5
27........	0	100	0	0	0	0	12	7	0	5
28........	80	100	0	0	0	0	15	5	0	5
29........	0	0	10	75	0	0	10	5	0	5
30........	0	—	0	0	0	0	5	—	5	80
31........	...	...	0	0	...	...	—	—	80	5

which observations could be made amount to 132 out of 135. The long periods of perfectly clear weather, permitting observations of the Sun to be made without interruption from day to day, should prove of the greatest importance in the study of many solar problems which require daily observations for their solution. From the records so far obtained, it seems probable that observations of the Sun could be made at Mount Wilson on more than 300 days in a year. In Los Angeles, during the past twenty-three years, the average number of "clear" days in the year is 317.

CLOUDINESS

Day of Month	September		October		November		December	
	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.
1	0	0	15	10	80	90	100	100
2	0	0	0	0	0	0	100	100
3	0	5	15	60	0	0	0	5
4	0	60	80	50	5	40	80	25
5	0	40	0	50	3	60	5	3
6	5	0	100	100	20	20	0	0
7	0	0	100	100	0	30	5	3
8	0	5	100	—	30	0	5	3
9	10	60	—	—	0	5	5	95
10	0	0	—	10	15	5	0	0
11	0	5	60	40	3	0	10	25
12	0	60	0	0	80	70	—	0
13	0	5	0	0	80	5	10	70
14	0	0	0	0	7	75	20	50
15	3	15	20	10	95	50	40	40
16	60	3	0	0	5	0	5	0
17	50	40	0	0	0	0	10	3
18	20	5	0	0	15	0	5	0
19	40	50	0	0	5	0	0	5
20	70	40	0	0	3	10	15	50
21	75	95	0	0	60	15	90	95
22	100	30	0	0	10	3	100	10
23	100	100	0	0	0	5	90	5
24	100	100	0	0	—	—	100	100
25	100	100	0	3	—	15	5	5
26	100	98	0	0	50	30	—	—
27	—	—	0	0	70	10	—	—
28	—	0	0	3	5	5	0	5
29	0	40	0	15	0	3	60	0
30	0	3	50	3	20	40	3	95
31	..	..	0	0	..	..	100	30

The cloudiness in July and August was due almost entirely to thunderstorms over the desert to the north and east. The clouds rarely reached our zenith and almost never interfered with the regular solar observations (cf. table of Seeing).

HUMIDITY

The question of humidity is of special importance in connection with the measurement of the solar constant, since water-vapor in the atmosphere absorbs very strongly the solar heat. The results obtained with a standard sling psychrometer, Weather Bureau pattern, are given in the following table:

RELATIVE HUMIDITY AT MOUNT WILSON

Day of Month	April		May		June		July		August	
	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.
1........	..	..	100	80	40	36	34	24	22	27
2........	..	..	57	80	39	39	23	38	22	33
3........	..	..	34	66	39	41	30	32	29	30
4........	..	..	46	49	24	25	38	56	32	40
5........	..	..	38	38	20	24	34	42	40	43
6........	..	..	29	40	27	42	45	43	34	43
7........	..	..	36	31	29	41	49	—	—	76
8........	..	..	18	22	23	29	33	18	64	58
9........	..	..	15	24	20	34	42	—	41	46
10........	..	..	22	41	21	21	—	—	28	35
11........	..	..	36	38	19	17	57	24	30	33
12........	..	..	36	54	—	—	29	40	53	65
13........	..	..	41	40	—	43	46	22	61	64
14........	..	..	32	64	52	42	25	25	67	72
15........	..	..	23	29	32	30	30	44	54	45
16........	..	..	27	19	34	30	50	—	37	36
17........	..	..	34	38	33	24	—	—	40	30
18........	—	85	25	66	32	41	—	16	34	45
19........	100	100	46	64	31	42	22	24	32	46
20........	..96	73	41	100	56	72	21	19	23	40
21........	60	79	42	45	45	53	—	42	37	33
22........	92	98	28	43	40	43	24	34	58	85
23........	63	65	37	32	44	54	35	35	79	79
24........	60	50	38	50	42	32	31	26	77	56
25........	29	68	100	100	30	27	33	50	69	58
26........	100	100	100	48	28	25	38	27	67	37
27........	100	100	37	38	27	36	31	50	40	43
28........	100	100	38	33	42	35	30	32	43	33
29........	46	36	23	15	35	30	50	46	21	29
30........	58	71	14	47	30	37	38	—	27	14
31........	..	..	30	35	..	..	—	—	14	31
Means...	77		43		34		33		43	

The marked dryness of the atmosphere on Mount Wilson during the summer months may be best appreciated by comparing these results with those obtained by the Weather Bureau at Washington during the corresponding period.

RELATIVE HUMIDITY AT WASHINGTON

Month	Mean	Maximum[1]	Minimum[1]
April............	63.0	100	30
May............	65.6	97	41
June............	77.8	98	54
July............	60.6	99	51
August...........	78.0	95	59

[1] Mean maximum and mean minimum humidity not determined.

RELATIVE HUMIDITY AT MOUNT WILSON

Day of Month	September		October		November		December	
	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.	8 A. M.	6 P. M.
1	26	29	47	38	62	46	100	100
2	38	24	49	48	84	89	100	100
3	31	38	42	37	72	83	70	57
4	43	43	60	63	71	53	63	49
5	31	22	69	100	49	53	58	52
6	22	25	100	100	63	57	53	47
7	20	18	100	100	38	57	59	43
8	30	40	100	—	52	35	47	59
9	41	39	—	—	37	51	57	51
10	53	48	—	86	56	61	12	14
11	48	45	100	100	54	26	12	17
12	60	63	53	56	48	44	19	42
13	57	63	53	47	61	30	48	43
14	51	28	56	60	22	21	33	30
15	37	43	67	77	28	56	18	—
16	41	27	67	55	57	50	—	21
17	32	66	49	54	72	41	20	30
18	54	78	44	52	71	81	26	35
19	60	37	59	66	59	35	42	28
20	46	49	67	68	60	34	29	34
21	32	67	33	31	69	29	42	65
22	93	93	20	27	59	57	100	84
23	94	100	22	34	55	47	91	95
24	100	100	24	28	—	—	100	100
25	100	100	23	27	—	32	81	81
26	100	80	26	34	65	41	—	—
27	—	—	29	47	31	29	—	—
28	—	64	46	71	53	50	56	45
29	60	52	41	66	36	40	50	56
30	57	47	66	81	49	62	38	90
31	..	.	78	40	..	..	100	83
Means	52		57		51		55	

The chief of the Weather Bureau has also kindly sent the following data as to the mean relative humidity at Washington for the remainder of the year. The two values refer to the results for 8 A. M. and 8 P. M., respectively. September, 84.8, 78.2; October, 80.8, 71.7; November, 76.2, 66.9; December, 77.8, 70.6.

TEMPERATURE

From March 25 to April 15 the temperature was recorded on a self-registering thermometer. After April 15 this record was supplemented by observations of maximum and minimum thermometers.

The results are given (in degrees Fahrenheit) in the following table. As bearing upon certain classes of night observations, the range of temperature between 8 P. M. and 4 A. M. is also included.

TEMPERATURE

Day of Month	April			May			June			July			August		
	Maximum	Minimum	Range 8 P. M. to 4 A. M.	Maximum	Minimum	Range 8 P. M. to 4 A. M.	Maximum	Minimum	Range 8 P. M. to 4 A. M.	Maximum	Minimum	Range 8 P. M. to 4 A. M.	Maximum	Minimum	Range 8 P. M. to 4 A. M.
1	..	..	..	49	32	8	76	46	4	93	57	5	83	57	3
2	..	..	..	56	27	4	82	53	1	81	58	5	90	63	5
3	..	..	..	64	39	4	89	55	2	79	56	8	91	66	3
4	..	..	..	70	42	5	80	56	7	80	56	3	89	66	5
5	..	..	..	79	45	7	81	59	5	77	54	6	91	66	2
6	..	..	..	80	55	2	78	57	6	75	55	6	92	68	2
7	..	.	..	84	51	8	75	48	9	—	—	5	—	—	6
8	..	..	..	84	55	7	79	52	3	76	52	6	83	64	3
9	..	..	..	85	57	5	83	57	4	—	—	2	87	60	6
10	.	..	..	86	57	5	82	61	5	—	—	2	86	64	4
11	..	..	.	79	57	2	87	60	4	82	57	5	87	63	4
12	..	..	.	85	54	2	—	—	5	86	56	4	88	62	5
13	..	..	..	75	56	4	—	—	5	89	59	3	85	64	3
14	..	..	..	79	50	6	77	57	6	83	63	7	83	60	3
15	..	..	..	85	53	4	80	54	4	75	57	4	86	60	2
16	..	..	..	82	57	4	79	53	5	72	50	4	87	60	5
17	..	..	..	79	56	5	81	56	5	84	63	6	87	62	5
18	53	37	6	75	49	4	83	55	8	93	61	1	88	63	4
19	42	35	3	56	36	8	79	59	5	95	66	3	93	64	5
20	41	23	6	74	45	1	73	51	7	91	69	1	90	65	5
21	49	34	1	78	50	5	86	50	1	—	—	2	86	59	8
22	46	32	5	81	51	4	83	55	2	82	62	4	77	60	2
23	49	25	9	78	56	3	78	55	6	89	62	2	78	56	2
24	63	36	3	69	54	4	78	53	6	91	66	3	81	56	0
25	64	40	4	52	38	10	87	56	3	88	68	4	85	61	2
26	43	29	8	53	35	3	88	62	1	82	66	3	89	62	3
27	43	23	4	69	41	0	85	63	5	88	62	2	87	64	2
28	44	31	0	75	49	5	79	57	4	83	68	5	87	62	2
29	63	36	2	71	50	5	79	55	3	83	62	7	87	62	2
30	65	41	5	70	46	6	78	53	5	—	—	3	81	59	4
31	—	—	—	77	45	4	—	—	—	—	—	4	82	59	3
Means	51.2	32.7	4.3	73.5	48.0	4.7	80.9	55.3	4.5	84.0	60.2	4.0	86.2	61.9	3.5
Daily r'ge	18.5		....	25.5		....	25.6		....	23.8		....	24.3		....

TEMPERATURE

Day of Month	September Maximum	September Minimum	September Range 8 P. M. to 4 A. M.	October Maximum	October Minimum	October Range 8 P. M. to 4 A. M.	November Maximum	November Minimum	November Range 8 P. M. to 4 A. M.	December Maximum	December Minimum	December Range 8 P. M. to 4 A. M.
1	87	60	3	79	60	5	75	48	2	60	38	4
2	90	66	2	83	54	5	63	42	7	48	36	4
3	91	66	3	84	55	4	78	40	3	59	33	4
4	89	63	5	87	59	2	71	46	3	64	35	2
5	93	65	5	66	47	3	70	45	2	60	29	7
6	97	67	4	56	37	8	72	46	1	63	31	3
7	97	69	4	49	39	2	80	49	3	64	33	2
8	87	68	5	—	—	0	84	49	2	61	37	1
9	87	63	7	—	—	2	82	51	2	66	37	2
10	83	59	7	67	—	2	82	52	3	74	41	1
11	83	59	3	56	43	7	76	47	5	72	42	4
12	86	57	3	72	36	4	69	49	7	68	37	5
13	85	58	4	74	45	4	72	42	3	70	36	4
14	87	58	1	71	48	5	72	48	1	66	44	1
15	83	59	2	67	43	5	64	44	3	—	44	5
16	81	59	3	75	43	4	74	38	6	66	52	—
17	74	50	4	75	39	6	73	47	2	65	41	2
18	71	44	5	77	42	2	67	45	3	67	49	2
19	78	49	2	82	46	3	76	42	5	69	42	3
20	76	50	3	84	46	4	78	47	2	67	50	2
21	72	52	3	81	50	4	80	50	3	60	39	3
22	51	41	7	83	53	4	73	50	3	44	32	5
23	51	39	4	79	54	4	72	49	2	45	33	2
24	54	41	2	82	54	2	—	—	1	41	35	2
25	52	43	1	82	54	3	72	—	1	50	31	5
26	52	36	6	78	52	3	77	51	3	—	—	3
27	—	—	2	74	47	6	73	52	2	—	—	3
28	75	—	3	72	47	3	73	50	3	56	34	5
29	82	50	3	67	47	1	75	49	2	59	44	3
30	81	52	5	67	46	2	72	45	2	54	38	4
31	..	..	..	75	43	3	..	..	..	43	33	4
Means	78.4	55.1	3.7	73.9	47.5	3.6	74.0	46.9	2.9	60.0	38.1	3.1
Daily range	23.3			26.4			27.1			21.9		

ATMOSPHERIC PRESSURE

No complete barometric record has been kept, since this did not seem of special importance in connection with the work. Nevertheless, an aneroid barometer has been read twice daily since July 13. The maximum and minimum readings recorded up to September 1 differed by only 0.22 inch.

WIND MOVEMENT

With such uniformity of atmospheric pressure, it might naturally be anticipated that the wind movement would be low. The results of anemometer readings (in miles), made with an instrument of the standard Weather Bureau pattern, are shown in the following table. The "day" results give the total movement from 8 A. M. to 6 P. M.; the "night" results give the total movement from 6 P. M. to 8 A. M.

Day of Month	April		May		June		July		August	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
1........	...	...	99	75	120	175	55	145	43	95
2........	...	...	49	165	71	141	71	102	50	72
3........	...	...	52	118	44	185	47	71	45	61
4........	...	...	29	88	44	114	34	41	46	48
5........	...	...	43	91	61	47	30	54	60	41
6........	...	...	30	62	78	108	43	78	43	49
7........	...	...	34	128	59	155	40	44	47	80
8........	...	...	43	106	55	146	49	85	33	63
9........	...	...	38	44	50	66	44	83	43	60
10........	...	...	44	133	52	86	43	77	62	78
11........	...	...	54	110	43	49	49	93	49	81
12........	...	...	35	101	32	75	31	74	58	122
13........	...	...	41	80	30	95	42	81	59	71
14........	..	...	39	95	23	133	42	59	44	73
15........	...	...	72	114	49	61	39	68	44	55
16........	...	..	42	110	56	80	33	50	45	80
17........	...	...	46	81	40	58	40	70	44	60
18........	..	...	50	56	37	56	32	62	26	55
19........	140	188	105	136	30	47	38	78	37	58
20........	62	70	45	48	36	74	63	91	36	100
21........	35	144	63	71	56	90	37	60	39	55
22........	40	42	66	82	37	56	43	37	63	104
23........	47	120	67	97	74	103	44	85	63	113
24........	32	109	69	79	44	86	60	64	55	101
25........	70	63	63	136	52	51	44	56	50	64
26........	91	191	33	60	55	59	39	71	35	66
27........	44	51	50	58	75	51	47	80	56	84
28........	33	34	21	101	42	52	41	57	54	107
29........	50	101	62	73	37	60	56	65	55	56
30........	47	63	51	80	56	46	57	131	57	69
31........	...	...	57	151	...	...	53	97	38	54
Total....	691	1,176	1,592	2,929	1,538	2,605	1,386	2,309	1,479	2,275
Means....	57.6	96.0	51.3	94.5	51.3	86.6	44.7	74.5	47.7	73.4
Hourly means	5.8	6.8	5.1	6.7	5.1	6.2	4.5	5.3	4.8	5.2

It appears from these results that the average wind movement is exceptionally low. The importance of this fact in its indication of a uniform atmosphere, and in connection with astronomical photog-

WIND MOVEMENT

Day of Month	September		October		November		December	
	Day	Night	Day	Night	Day	Night	Day	Night
1	34	76	43	60	61	71	27	81
2	51	30	39	32	42	123	36	70
3	52	67	38	58	44	130	34	82
4	40	70	50	81	55	47	42	137
5	49	71	58	100	38	88	80	120
6	50	97	44	125	41	95	40	141
7	51	48	85	56	38	64	42	78
8	50	88	—	129	48	97	36	62
9	47	68	—	—	41	144	38	66
10	35	54	—	—	36	151	66	106
11	37	53	68	86	32	45	37	59
12	42	44	40	102	35	148	65	165
13	46	73	41	52	25	53	38	154
14	47	71	53	83	49	46	38	56
15	66	86	40	117	35	105	53	69
16	73	81	50	79	37	71	39	68
17	51	101	89	207	56	93	31	56
18	33	91	50	139	44	92	31	53
19	38	83	65	128	39	48	33	64
20	36	71	47	194	29	51	37	51
21	80	52	37	125	39	73	85	74
22	37	110	46	45	59	110	64	101
23	83	84	45	44	65	141	36	46
24	72	161	36	74	—	—	82	113
25	70	163	38	66	—	—	66	142
26	64	101	36	55	53	91	—	—
27	—	—	42	49	46	91	—	—
28	—	—	53	62	45	47	37	69
29	64	158	64	94	47	73	57	48
30	58	53	39	66	65	165	122	146
31	..	..	42	73	..	..	60	200
Means	52.0	82.3	49.2	89.0	44.4	91.2	50.1	92.3
Hourly means	5.2	5.9	4.9	6.4	4.4	6.5	5.0	6.6

raphy, will be appreciated by astronomers. The shaking of a large instrument by the wind is frequently so serious as to reduce greatly the quality of astronomical photographs obtained in windy weather. At Mount Wilson, where a dead calm is an exceedingly common occurrence, all of the most exacting requirements of astronomical photography are completely realized.

TRANSPARENCY OF THE ATMOSPHERE

I have previously alluded to the dust-storms which sometimes enter the San Gabriel Valley through the Cajon Pass from the Mojave Desert, and those much rarer storms in which the dust is carried by

the wind completely over the Sierra Madre Mountains. In the more common form of dust-storm (the so-called "Santa Ana") the dust enters the valley in a fairly well-defined mass and proceeds westward along the cañon of the Santa Ana River. In approaching the coast it spreads over a large area and diffuses itself with tolerable uniformity through the lower atmosphere. I have seen from Mount Wilson a dust-storm in the region of Riverside, which in twenty-four hours had spread itself over Los Angeles and Pasadena. When it reached this part of the valley there was almost no wind, and the dust seemed to diffuse itself through the air. Such storms sometimes completely hide the Sierra Madre Mountains from observers in Pasadena. Fortunately they are almost always confined to the lower atmosphere, and do not appreciably affect the transparency of the sky above Mount Wilson, where daily observations show that the transparency of the day and night sky are very satisfactory.

SEEING

Systematic tests of the definition of the solar image have been made on Mount Wilson with a telescope of $3\frac{1}{4}$ inches aperture, with an eyepiece giving a power of about 100 diameters. At first the character of the seeing was rated on a scale of 5; but it soon appeared that a scale of 10 would be preferable under the existing conditions. Accordingly, the seeing as recorded in the following table is given on a scale of 10. Seeing 8, which is so frequently obtained during the early morning hours, represents a sharply defined image of the Sun, showing the granulation and the details of the spots with great distinctness, and indicating practically no trembling at the limb. Such seeing occurs at the Yerkes Observatory only occasionally, although that observatory seems to be better situated than many other institutions for work on the Sun.

An examination of the table will show that the seeing is best during the early morning hours, although the image is frequently very good in the late afternoon. Shortly after sunrise the Sun's limb is serrated, but this effect becomes less and less marked as the Sun's altitude increases. Usually, at this time in the morning, the atmosphere is almost perfectly calm and cloudless. The seeing usually improves and reaches a maximum, where it remains for some time. The effect

SEEING

April	Hour of Observation									April	Hour of Observation								
	6	7	8	9	10-2	3	4	5	6		6	7	8	9	10-2	3	4	5	6
1...	–	5	5	4	4	4	5	4	–	16...	–	5	–	5	–	–	–	4	–
2...	–	–	5	6	5	5	4	4	–	17...	–	–	5	4	4	6	6	–	–
3...	–	5	6	7	6	–	–	–	–	18...	–	6	7	–	–	–	–	–	–
4...	–	5	6	7	6	3	5	–	–	19[1]..	–	–	–	–	–	–	–	–	–
5...	–	8	8	8	7	–	8	8	6	20...	–	6	5	–	–	–	–	–	–
6...	–	6	7	6	4	7	7	5	–	21...	–	6	7	6	5	4	6	6	–
7...	–	9	8	7	7	6	7	7	5	22[1]..	–	–	–	–	4	–	–	–	–
8...	–	–	7	–	–	–	–	–	–	23...	–	–	5	4	4	4	4	–	–
9...	–	5	5	4	4	4	5	4	–	24...	–	–	7	6	5	5	6	6	7
10...	6	7	7	6	6	7	–	–	–	25...	–	–	–	–	4	4	4	4	–
11...	7	9	7	6	6	7	–	–	–	26[2]..	–	–	–	–	–	–	–	–	–
12...	–	7	7	6	–	–	–	–	–	27[1]..	–	6	4	–	–	–	–	–	–
13...	–	8	8	7	–	–	7	8	7	28[1]..	–	6	–	–	–	–	–	–	–
14...	–	6	6	6	5	5	4	–	–	29...	–	7	6	6	4	5	6	–	–
15...	–	–	–	–	–	–	–	–	–	30...	6	7	4	4	4	4	6	–	–

May	Hour of Observation									June	Hour of Observation								
	6	7	8	9	10-2	3	4	5	6		6	7	8	9	10-2	3	4	5	6
1[2]..	–	–	–	–	–	–	–	–	–	1[3]...	–	–	–	–	–	–	6	–	–
2...	–	5	4	4	3	2	2	2	–	2...	–	–	7	6	6	6	6	6	–
3...	–	7	6	7	5	4	6	–	–	3...	–	6	6	6	6	6	6	6	–
4...	–	6	6	5	4	5	5	–	–	4...	–	6	–	7	5	–	–	–	–
5...	–	7	–	–	4	5	5	4	–	5...	–	8	8	–	7	–	6	–	4
6...	7	8	6	–	–	–	–	–	–	6...	–	9	9	8	7	7	–	–	–
7...	5	4	4	4	4	4	4	4	–	7...	–	7	–	–	4	4	6	–	7
8...	–	7	7	5	–	–	–	–	–	8...	–	8	8	–	6	–	–	7	6
9[3]..	–	–	5	–	–	–	–	–	–	9...	–	9	8	6	6	–	6	7	–
10...	–	5	6	5	5	–	–	–	–	10...	–	9	8	–	7	–	–	7	–
11...	–	6	5	5	4	–	–	–	–	11...	–	9	8	–	6	–	8	7	9
12...	–	–	–	–	–	–	–	–	–	12...	–	9	–	–	–	–	–	–	–
13...	–	–	–	–	–	–	–	–	–	13...	–	–	–	–	–	–	–	–	–
14...	–	–	–	–	–	–	–	–	–	14...	–	–	–	–	–	–	–	8	–
15...	–	5	6	5	–	–	–	–	–	15...	–	9	8	7	6	–	7	7	–
16...	6	–	–	7	7	–	6	6	–	16...	–	9	8	–	7	–	8	7	8
17...	–	–	–	–	–	–	–	–	–	17...	–	9	9	7	7	5	–	7	8
18...	–	–	–	–	–	–	–	–	–	18...	–	8	7	–	5	–	7	8	7
19...	–	–	–	–	–	–	–	–	–	19...	–	9	6	6	4	–	–	7	–
20...	–	–	–	–	–	–	–	–	–	20...	6	6	–	6	5	7	7	–	6
21...	–	–	–	–	–	–	5	–	–	21...	–	6	6	–	5	–	6	–	6
22...	–	6	7	8	–	4	–	–	–	22...	8	–	8	6	6	6	7	8	8
23...	–	6	–	6	5	–	6	–	–	23...	–	8	7	–	7	–	7	8	–
24...	–	8	–	6	6	–	5	–	–	24...	–	9	8	–	6	–	7	8	–
25[1]..	–	–	–	–	–	–	–	–	–	25...	8	9	7	–	7	–	7	7	–
26[1]..	–	–	–	–	–	–	–	8	–	26...	–	9	8	8	6	–	6	6	–
27...	–	8	7	6	6	7	7	8	–	27...	–	8	8	7	7	–	–	5	6
28...	–	8	8	–	7	–	8	–	7	28...	8	8	–	–	6	–	6	6	–
29...	–	9	8	8	8	–	–	–	–	29...	8	9	–	6	6	–	–	8	–
30...	–	7	8	8	7	6	6	7	–	30...	8	9	–	8	8	8	8	8	7
31...	–	6	7	–	6	6	7	–	–										

[1] Rain. [2] Snow. [3] Cloudy.

July	Hour of Observation									August	Hour of Observation								
	6	7	8	9	10-2	3	4	5	6		6	7	8	9	10-2	3	4	5	6
1...	–	5	–	6	–	–	6	6	–	1...	–	–	–	6	5	6	7	8	–
2...	–	8	–	–	4	–	–	–	–	2...	6	6	6	–	4	6	7	6	–
3...	–	8	7	–	6	–	–	–	4	3...	–	7	–	–	5	–	7	7	–
4...	–	6	–	7	5	–	–	–	–	4...	–	6	7	7	6	6	6	7	–
5...	8	8	–	–	5	–	7	–	6	5...	–	8	8	–	5	5	–	–	–
6...	–	8	8	–	7	–	–	8	8	6...	8	8	7	6	–	–	–	–	–
7...	–	8	7	–	–	–	–	–	–	7...	–	8	–	–	–	–	–	–	–
8...	8	8	7	–	7	–	–	8	8	8...	–	8	–	–	5	6	6	6	–
9...	8	9	–	–	6	–	–	–	–	9...	6	7	–	6	4	–	7	8	8
10...	–	–	–	–	–	–	–	–	–	10...	6	7	7	–	5	6	–	6	–
11...	–	8	6	–	5	–	7	8	6	11...	7	7	6	–	5	6	–	6	–
12...	8	9	8	–	5	6	7	7	7	12...	6	5	–	–	5	6	–	6	–
13...	8	8	7	7	6	–	–	8	7	13[4]....	6	–	–	–	–	–	–	4	–
14...	8	8	7	–	6	–	7	7	7	14[4] ..	–	7	–	–	–	–	–	–	–
15...	–	7	6	5	4	4	6	7	–	15...	–	7	–	–	–	–	8	–	6
16...	–	5	4	4	–	–	–	–	–	16...	8	7	–	–	4	–	8	–	7
17...	–	–	–	–	–	–	–	–	–	17...	–	8	7	–	7	–	7	7	–
18...	8	8	8	7	6	–	–	–	–	18...	8	7	6	–	5	–	7	7	–
19...	6	8	7	7	6	–	–	–	–	19...	7	8	–	–	6	–	7	7	–
20...	7	8	7	6	4	–	6	8	7	20...	5	6	6	–	6	–	6	6	–
21...	–	–	–	–	–	–	–	–	–	21...	–	8	8	–	6	–	7	–	6
22...	–	7	–	6	5	–	6	7	–	22[1] ..	–	–	–	6	–	–	–	–	–
23...	–	7	–	6	5	–	6	7	–	23...	–	–	8	–	–	–	–	7	–
24...	–	7	–	–	–	–	–	–	–	24...	–	6	–	–	5	–	–	6	–
25...	–	6	5	4	4	4	5	–	–	25...	8	7	6	–	5	–	6	–	6
26...	–	–	6	5	4	5	6	7	–	26...	–	9	7	–	5	–	7	–	6
27...	–	6	5	4	4	5	6	7	–	27...	8	8	7	–	6	–	7	–	6
28...	7	8	7	–	4	–	–	4	–	28...	–	8	7	6	5	–	7	6	–
29...	–	7	6	–	4	–	8	7	–	29...	–	8	7	–	5	–	–	–	7
30...	–	8	7	6	6	–	–	–	–	30...	–	8	7	–	5	–	–	–	7
31...	–	–	–	–	–	–	–	–	–	31[3] ..	–	3	–	–	–	8	–	6	–

of the heating of the mountain then becomes apparent and the definition deteriorates. The disturbances at the Sun's limb under these conditions do not resemble those seen immediately after sunrise, but have a fluttering appearance, which we are accustomed to speak of as the "heating effect." In the late afternoon the seeing usually improves, but it is rarely very good at midday. This is not a rule without exceptions, however, as we have sometimes recorded nearly perfect definition during the hottest hours of the day.

Everyone who has noted the heated air above the surface of the ground will wonder, in considering the effect of such disturbances upon solar observations, whether these disturbances rise to a great height. A casual observation is sufficient to show that the disturb-

[1] Rain [2] Snow [3] Cloudy [4] Storm.

SEEING

September	Hour of Observation							October	Hour of Observation						
	7	8	9	10-2	3	4	5		7	8	9	10-2	3	4	5
1	8	6	–	5	–	7	7	1	7	6	–	5	–	7	6
2	7	8	6	5	–	7	6	2	8	7	–	5	–	–	–
3	8	6	6	5	–	–	7	3	8	7	6	5	–	7	–
4[3]	8	7	–	–	–	–	6	4[3]	–	–	–	–	–	6	–
5[3]	7	6	–	–	6	–	–	5[5]	8	–	–	–	–	–	–
6	8	7	6	5	–	–	7	6[9]	–	–	–	–	–	–	–
7	8	7	6	5	6	–	–	7[9]	–	–	–	–	–	–	–
8	8	7	–	5	–	7	7	8[9]	–	–	–	–	–	–	–
9	8	7	6	5	6	–	–	9[9]	–	–	–	–	–	–	–
10	8	–	6	5	–	7	6	10[9]	–	–	–	–	–	6	–
11	7	7	6	5	–	7	7	11[5]	7	6	–	–	–	–	–
12[3]	8	7	–	–	–	–	–	12	7	8	7	5	–	6	–
13	8	6	–	5	5	–	–	13	6	8	6	6	–	6	–
14	7	6	–	5	–	–	4	14	7	8	7	6	–	7	–
15	8	7	–	5	–	–	6	15	7	7	–	5	–	6	–
16	7	6	–	5	–	7	6	16	6	7	–	6	–	–	–
17[3]	7	6	–	–	–	–	–	17	6	6	–	5	–	6	–
18[5]	7	6	–	–	–	–	–	18	6	6	–	6	–	6	–
19	7	7	–	5	–	–	7	19	6	7	–	6	–	6	–
20[3]	7	6	–	–	–	–	–	20[6]	3	–	6	5	–	–	5
21[3]	–	–	–	–	–	–	–	21	6	6	–	5	–	6	–
22[9]	–	–	–	–	–	–	–	22	7	8	7	5	–	6	–
23[9]	–	–	–	–	–	–	–	23	7	7	7	5	–	6	–
24[9]	–	–	–	–	–	–	–	24	8	8	–	6	7	6	–
25[9]	–	–	–	–	–	–	–	25	7	8	–	6	6	8	–
26[9]	–	–	–	–	–	–	–	26	7	8	–	6	6	–	–
27	–	–	–	–	–	–	–	27	6	7	–	5	6	–	–
28	–	–	–	–	–	–	–	28	6	8	–	5	–	–	–
29	7	–	6	5	–	7	–	29	8	8	6	5	–	–	–
30	7	6	–	5	–	6	–	30[3]	–	–	5	5	8	7	–
								31	8	7	–	5	7	–	–

ance decreases rapidly in passing upward from the ground, but it is, of course, quite impossible to determine by means of the unaided eye the probable effect of this disturbance on telescopic observations. We have accordingly made many observations of the Sun with the $3\frac{1}{4}$-inch telescope supported in a pine tree at heights above the ground ranging from 20 to 80 feet. The results of these observations clearly indicate that a telescope employed in solar work should be mounted as high above the ground as circumstances warrant. At the lower elevations in the tree the advantage over positions still nearer to the ground was sometimes not appreciable; but at a height of 80 feet above the ground the improvement in definition was very distinct. Probably

[3] Cloudy. [5] Fog. [6] High wind. [9] Fog and rain.

SEEING

November	Hour of Observation							December	Hour of Observation						
	7	8	9	10-2	3	4	5		7	8	9	10-2	3	4	5
1[3]	–	–	–	6	6	6	–	1[5]	–	–	–	–	–	–	–
2[3]	5	–	–	–	6	–	–	2[5]	–	–	–	–	–	–	–
3	6	6	–	5	6	–	–	3[7]	6	–	–	–	–	–	–
4[3]	8	7	–	5	–	–	–	4[3]	–	–	–	–	–	–	–
5	7	7	–	5	–	–	–	5[8]	–	5	–	–	–	–	–
6	–	8	7	5	6	–	–	6	5	6	–	5	5	–	–
7	7	7	–	6	6	–	–	7	–	6	–	6	6	–	–
8	7	–	–	5	6	–	–	8	–	6	–	5	6	–	–
9	6	–	–	5	6	–	–	9	–	7	–	6	6	–	–
10	5	6	–	5	5	–	–	10	–	–	–	–	–	–	–
11	6	8	–	5	5	–	–	11	–	–	–	–	–	–	–
12[3]	–	–	–	–	–	–	–	12	–	–	–	–	–	–	–
13[3]	–	–	–	–	6	–	–	13	–	6	6	5	6	–	–
14	6	6	–	5	–	–	–	14	–	7	–	5	6	5	–
15	–	–	–	–	6	–	–	15	–	6	–	5	5	–	–
16	7	7	–	5	6	–	–	16	–	8	7	6	6	–	–
17	8	7	–	6	6	–	–	17	–	8	–	6	6	–	–
18	7	7	–	5	6	–	–	18	–	8	–	6	7	–	–
19	7	8	–	6	–	–	–	19	–	8	7	5	6	–	–
20	–	7	6	6	6	–	–	20[3]	–	7	–	–	–	–	–
21	7	7	–	6	–	–	–	21[3]	–	–	–	–	–	–	–
22	7	8	–	6	7	–	–	22[9]	–	–	–	–	–	–	–
23	7	7	–	6	7	–	–	23[9]	–	–	–	–	–	–	–
24	–	–	–	–	–	–	–	24[9]	–	–	–	–	–	–	–
25	–	–	–	–	–	–	–	25	–	–	6	–	6	–	–
26	6	7	–	5	–	–	–	26	–	–	–	–	–	–	–
27[3]	–	–	–	5	6	–	–	27	–	–	–	–	–	–	–
28	7	7	–	5	7	–	–	28	–	7	6	5	6	–	–
29	7	7	7	6	5	–	–	29	–	8	7	6	6	–	–
30[3]	–	6	–	–	–	–	–	30[3]	–	–	7	–	–	–	–
								31[9]	–	–	–	–	–	–	–

this is one of the reasons why the solar definition with the 40-inch Yerkes telescope averages considerably better than we expected it would, for with this telescope the object-glass is over 70 feet above the ground.

OBSERVATIONS WITH THE FIFTEEN-INCH CŒLOSTAT TELESCOPE

In March 1904 a cœlostat of 15 inches aperture was sent to Mount Wilson from the Yerkes Observatory. This instrument had previously been employed by Professors Barnard and Ritchey, of the Yerkes Observatory party, at the solar eclipse of May 28, 1900, in Wadesboro, N. C., and by Professor Barnard at the Sumatra eclipse

[3] Cloudy. [5] Fog. [7] Partly cloudy. [8] Cold and windy. [9] Fog and rain.

in 1901. As used at Mount Wilson, it is supplied with a second plane mirror, mounted south of the cœlostat, and arranged to slide on a north-and-south track in such a way as to receive the solar rays corresponding to any declination of the Sun.

The rays are reflected from this mirror toward the north to a 6-inch photographic objective of 61½ feet focal length, mounted on the extension of the stone pier just above the cœlostat. After passing through this lens the rays traverse a long tube built of wooden framework and covered with paper. The solar image is formed within a small house which terminates this tube at its north end. In the house a photographic plate-holder is mounted, in conjunction with a slide containing a narrow slit, which can be shot at high speed across the solar image by means of a spring. In this way the very short exposure required for direct photography of the Sun can be obtained.

One of the chief points of interest connected with this instrument is the effect of the heating of the air within the tube upon the definition of the solar image. In the first experiments with this apparatus, the skeleton tube was covered on all sides with tar-paper, just as it had been used in the eclipse work. Above the tube, and separated from it by a considerable air-space, was a canvas fly for the purpose of shielding the tube from the direct rays of the Sun. It was found that in the early morning, before the tube had become heated, the definition of the solar image was excellent. In a short time, however, heated air within the tube completely spoiled the definition, and the Sun's image became so blurred and indistinct that no observations of value could be made with it. These circumstances led us to question what the effect would be if no tube were employed. The 6-inch lens was therefore mounted in such a position as to throw the beam horizontally through the air toward the north, outside of the tube and over that portion of the ground which was in shadow. The image observed under these circumstances was found to be much better defined than that seen through the heated air of the tube. We accordingly decided to try the experiment of taking off all of the paper on the two sides which formed the upper half of the tube. It also seemed advisable to stretch the canvas fly at a much greater distance from the tube and to provide means of exit at the top for any heated air which might be found under the fly. As soon as the tube and fly had been re-arranged

in this manner, a great improvement was immediately noticed. The definition of the image became much better and the deterioration observed in the previous instance was no longer seen. The air in the tube remained cool, whereas before it had become greatly heated.

These experiments would seem to throw some light on the question of designing suitable tubes and shelters for telescopes used in a horizontal, or nearly horizontal, position. It seems likely that if the cœlostat and the instruments used with it could be mounted on piers at a height of 70 feet or more above the ground, it would be unnecessary to use any tube, particularly if the ground below the path of the beam were shielded from the Sun by a light canvas cover, stretched at a height of several feet above the surface and suitably ventilated. Of course, the practical difficulties in such a construction are very considerable, on account of the great cost and the lack of stability of high piers. For the Snow telescope it therefore seemed advisable to design a special form of house, in the hope of securing good definition with a solar beam at a moderate height above the ground. Experiments made with the 15-inch cœlostat seem to show that this latter instrument is too near the ground for the best results, although it gives excellent definition in the early morning, before the heating of the soil is very great.

The design of the house now under construction for the Snow telescope will be described in a subsequent report. It may be said here, however, that it consists of a skeleton frame of light steel construction, provided with a ventilated roof. The floor is to be of canvas, tightly stretched at a height of one foot above the ground and permitting a free circulation of air below. The inner walls of the house (which is 10 feet wide at its narrowest point) are to be of light canvas, so arranged that they can be raised or lowered at will. The outer walls of the house are to be covered by canvas louvres, so arranged as to shield the entire house from the direct rays of the Sun, and permitting a free circulation of air. The stone pier, 27 feet high, on which the cœlostat will stand, is also to be shielded from the Sun by canvas louvres. The ground surrounding the instrument is fairly well covered with bushes, and the few bare spots can be covered with stretched canvas, if necessary.

Spectroscopic observations.—The spectroscope used with the

cœlostat telescope is of the Littrow form: a single lens, of 4 inches aperture and 18 feet focal length, serves at once as collimator and camera lens. After passing through the slit, which is mounted in the focal plane of the photographic objective employed with the cœlostat, the rays pass to the 4-inch objective, by which they are rendered parallel. They then meet the 4-inch Rowland plane grating, having 14,438 lines to the inch, from which they are returned through the 4-inch objective. The image of the spectrum is formed on a photographic plate, mounted in the focal plane and a little to one side of the slit. This apparatus is giving excellent definition, surpassing that of any spectroscope employed at the Yerkes Observatory.

The character of the results obtained with this spectroscope, and its convenience of manipulation, illustrate one of the arguments in favor of fixed telescopes of the cœlostat type, as contrasted with moving equatorial telescopes. At the Yerkes Observatory it has never been possible to attach a sufficiently long and powerful spectroscope to the moving tube of the 40-inch refractor. Such a spectroscope must be mounted in a fixed position on substantial piers, and the telescope must be so constructed as to permit a sharp and well-defined image of the Sun to be maintained in a fixed position on the slit. This can readily be accomplished with the aid of a cœlostat, provided only that the difficulties peculiar to this type of telescope can be overcome. From the experiments so far made, we believe that the difficulties can be surmounted and that the fixed telescope is certain to become an instrument of great importance in the future.

CONCLUSION

From the observations given in this paper, it appears that Mount Wilson meets in a very remarkable degree the requirements of a site for a solar observatory. Indeed, I know of no other site that compares at all favorably with it. If a large solar observatory were established there, it might be expected to yield many important results, not to be obtained under less favorable conditions.

THE SOLAR OBSERVATORY OF THE CARNEGIE INSTITUTION OF WASHINGTON

By GEORGE E. HALE

In a report entitled "A Study of the Conditions for Solar Research at Mt. Wilson, California"[1] I have outlined the circumstances that have resulted in the establishment of a Solar Observatory on Mount Wilson[2] by the Carnegie Institution of Washington. At the recent annual meeting of the board of trustees, a grant of $150,000 was authorized, for use during 1905. It is expected that the first equipment will cost about twice this sum, and that important additions will result in the future from the operation of a large and well-appointed instrument and optical shop.

In April 1904 a grant of $10,000 was made by the executive committee of the Carnegie Institution for the purpose of bringing the Snow telescope to Mount Wilson from the Yerkes Observatory. An expedition for solar research was accordingly organized under the joint auspices of the University of Chicago and the Carnegie Institution, with the understanding that the funds granted by the Carnegie Institution would be used for the construction of piers and buildings, and for other expenses incidental to the work, while the University of Chicago would furnish the instrumental equipment, and pay the salaries of some of the members of the party. Messrs. Ritchey, Ellerman, and Adams, of the staff of the Yerkes Observatory, were to be associated with me in the work. While the executive committee of the Carnegie Institution indicated its intention of supplying further funds, if possible, for use during 1905, it was not supposed in April that provision could be made at present for the establishment of a large and fully equipped solar observatory. Nevertheless, it was agreed with the University of Chicago that if at any

[1] See *Contributions from the Solar Observatory of the Carnegie Institution* No. 1; *Astrophysical Journal*, March 1905.

[2] The approximate geographical position of the Solar Observatory, as given (by triangulation) by the U. S. Coast and Geodetic Survey, is as follows:

Latitude, $34° \; 13' \; 26''$
Longitude, $118° \; 3' \; 40''$.

time the Carnegie Institution should decide to establish a solar observatory of its own, such an observatory would take the place of the Mount Wilson Station of the Yerkes Observatory, and the work of the Station would be continued under the sole auspices of the Carnegie Institution.

AIM OF THE SOLAR OBSERVATORY

It has been my privilege to outline the plan of research and to determine the equipment of two other observatories. The Kenwood Observatory (subsequently merged with the Yerkes Observatory) had for its prime purpose the development of the spectroheliograph, and its use in solar research. The equipment was consequently designed with this purpose in view. The Yerkes Observatory had its origin in the gift of a 40-inch refracting telescope to the University of Chicago by Mr. Charles T. Yerkes. In designing the Observatory building, and in preparing a plan of research, I felt that the obligation of securing the greatest possible return from this powerful telescope must be a paramount consideration. In the nature of the case, a thoroughly homogeneous scheme of investigation could hardly be adopted for the Observatory under these circumstances, since the lines of work for which the 40-inch telescope is peculiarly fitted are very diverse in character.[2] The various applications of the Yerkes telescope in micrometric observations by Professors Burnham and Barnard; in stellar spectroscopy by Professor Frost and Mr. Adams, and by Mr. Ellerman and myself; in lunar, nebular, and stellar photography by Professor Ritchey; in the photographic study of stellar parallaxes by Dr. Schlesinger; in stellar photometry by Mr. Parkhurst; and in solar research with the spectroheliograph by Mr. Ellerman, Mr. Fox, and myself, will suffice to indicate that a serious attempt has been made at the Yerkes Observatory to realize the full possibilities of this magnificent instrument. But while recognizing the special demands of the 40-inch telescope, I have constantly kept in mind the development of other departments of the Observatory's work. Without enumerating these,[1] I shall confine my remarks to a line of effort which is of importance in the present connection,

[2] See "The Aim of the Yerkes Observatory," an address delivered at the formal inauguration of the work in 1897. *Astrophysical Journal*, **6**, 310, 1897.

[1] The results accomplished are epitomized in the *Reports of the Director*.

since it has defined the chief elements in the plan of research of the new Solar Observatory.

Both in the Kenwood and the Yerkes Observatories the instrument shop was regarded as of great importance, since it alone rendered possible the construction and frequent improvement of instruments of new type or special design. The Rumford spectroheliograph, the Bruce spectrograph, the two-foot reflecting telescope, and the Snow telescope are among the products of this shop. The operations of the shop were not confined to the construction of the mechanical parts of instruments; provision was also made for optical work on a large scale, under the direction of Professor G. W. Ritchey, who also succeeded Professor F. L. O. Wadsworth in the direction of the mechanical work.

In 1896, recognizing the great possibilities of the reflecting telescope for astrophysical research,[1] I engaged Professor Ritchey for the purpose of constructing a mirror of five feet aperture. An account of the methods employed in the grinding of this mirror has recently been given by Professor Ritchey.[2] My father's hope that he might be able to provide a suitable mounting for the five-foot mirror was frustrated by his death in 1898. At that time the fine grinding of the spherical surface had been completed, and the demands of other optical work rendered it advisable to discontinue further operations until funds for a mounting could be obtained. Many attempts were made to secure these funds, but they all proved ineffectual. Meanwhile, the success achieved by Keeler and Perrine with the three-foot Crossley reflector, and the remarkable results obtained by Ritchey with the two-foot reflector of the Yerkes Observatory, directed renewed attention to the possibilities of reflecting telescopes. It soon became clear that a five-foot mirror, if properly mounted, would give results entirely beyond the reach of existing instruments. The committee of the Carnegie Institution on the projects for southern and solar observatories accordingly felt that such a telescope should be included in the Solar Observatory equipment. The figuring and mounting of the five-foot mirror will therefore be undertaken as soon as possible.

[1] "On the Comparative Value of Reflecting and Refracting Telescopes for Astrophysical Investigations," *Astrophysical Journal*, **5**, 119, 1897.

[2] *Smithsonian Contributions to Knowledge*, Vol. XXXIV.

It is a fortunate circumstance that the construction and use of a great reflecting telescope is a logical element in the general plan of research laid down for the Solar Observatory. In *Year Book* No. 2,[1] of the Carnegie Institution may be found a report on this subject, prepared at the request of Professors Boss and Campbell, my colleagues on the committee, and improved in many particulars as the result of their criticisms. The prime object of the Solar Observatory is to apply new instruments and methods of research in a study of the physical elements of the problem of stellar evolution. Since the Sun is the only star near enough the Earth to permit its phenomena to be studied in detail, special attention will be devoted to solar physics. It is hoped that the knowledge of solar phenomena thus gained will assist to explain certain stellar phenomena. Conversely, the knowledge of nebular and stellar conditions to be obtained through spectroscopic and photographic investigations with the five-foot reflector should throw light on the past and future condition of the Sun. All of the principal researches will thus be made to converge on the problem of stellar development. The name "Solar Observatory" is regarded as appropriate, since the spectroscopic study of stars and nebulæ, to be carried on in connection with the solar work, are essential elements in any attempt to determine the mode of origin, the development, and the decay of the Sun as a typical star.

How, then, shall we attack in an effective manner the complex problem of stellar evolution? It goes without saying that I can offer no general answer to this question; I can only point out the three principal lines of attack which we hope to pursue at the Solar Observatory. These involve:

1. The more complete realization of laboratory conditions in astrophysical research, through the employment of fixed telescopes of the cœlostat type, and through the adoption of a *coudé* mounting for the five-foot reflector. This should permit: (*a*) the use of mirrors or objectives of great focal length, thus providing a large image of the Sun for study with spectroscopes and spectroheliographs; (*b*) the use of long focus grating spectroscopes, mounted in a fixed position in constant temperature laboratories, for the photography of stellar spectra requiring very long exposures; (*c*) the use of various labora-

[1] Page 49.

Lower Part of Mount Wilson Trail, Showing Pack Animals Loaded with Lumber

tory instruments, such as the radiometer, which cannot be employed in conjunction with moving telescopes.

2. The development of the spectroheliograph in the various directions suggested by recent work at the Yerkes Observatory, including the photography of the entire solar disk with dark lines of hydrogen, iron, and other elements; further application of the method of photographing sections of flocculi corresponding to different levels; special studies of sun-spots, etc.; and daily routine records of calcium and hydrogen flocculi and prominences.

3. The construction of a five-foot equatorial reflector, with *coudé* mounting, and its use in the photography of nebulæ, the study of stellar and nebular spectra, and the measurement of the heat radiation of the brighter stars.

It was originally intended that a prolonged series of determinations of the solar constant, extending over at least one sun-spot period, should be made an important feature of the Observatory's work. The plans outlined in *Year Book* No. 2 accordingly included an equipment at Mount Wilson for this purpose, and suggested, in harmony with Dr. Langley's view, that provision be made for two additional stations, one near the summit of a high mountain, at an elevation of about 12,000 feet, the other at a much lower level on the same mountain. The principal purpose of these two stations was to measure the atmospheric absorption, in order to eliminate it from the solar constant determinations. The recent developments of Dr. Langley's researches at Washington have led Mr. Abbot, who is associated with Dr. Langley in the work, to the conclusion that entirely satisfactory results can be obtained there by the method employed. The poor atmospheric conditions with which the Washington observers have so successfully contended, and the disturbances arising from ground tremors in the heart of a large city, would be largely eliminated at Mount Wilson. For this reason it seems probable that results of higher precision could be obtained at this site. I have accordingly offered Dr. Langley facilities for pursuing the investigation at Mount Wilson, which I trust he may find it possible to accept.

In addition to the above-mentioned observations, provision will be made at Mount Wilson for various laboratory investigations necessary in conjunction with solar research. In view of the impor-

tance of securing a complete record of solar phenomena when magnetic storms are in progress, suitable magnetic apparatus, recommended by Dr. L. A. Bauer, in charge of the Department of Terrestrial Magnetism of the Carnegie Institution, will be installed at a sufficient distance from the electrical machinery.

TRANSPORTATION OF MATERIAL

The first problem that confronts one in undertaking the construction of buildings and the erection of instruments on Mount Wilson is that of transportation over the trail from the valley. Two trails are available—the "Old Trail," from Sierra Madre, and the "New Trail," from the foot of Eaton Cañon, six and one-half miles from Pasadena. The New Trail, which is much the better of the two, is about nine miles long. At its narrowest points it is little over two feet in width, and in some of these places it had to be widened before the transportation of the heavy parts of the Snow telescope could be attempted. For ordinary packing with "burros" (donkeys) or mules the trail is well adapted. The loads brought up in this way range from 80 to 225 pounds per animal, and the charges from $1 to $1.35 per hundred pounds. On account of the expense of transportation over the trail, the best cement costs on the mountain more than twice as much as in the valley.

With a single exception, all parts of the 15-inch cœlostat, which was erected on Mount Wilson in April 1904,[1] were brought up on animals. The equatorial head of this instrument, which weighs about four hundred pounds, is too heavy to be carried in this way. A carriage was accordingly improvised for it from a two-wheel truck, such as is used by the railway companies for trunks. This served the purpose fairly well, though two days were required for the trip up the mountain. It was evident that a different arrangement would be required for heavier castings.

After provision had been made for the use of the Snow telescope on Mount Wilson, the carriage shown in Plate IX was designed. The running gear consists of four automobile wheels, 28 inches (71 cm) in diameter, with $2\frac{1}{2}$ inch (6.3 cm) rubber tires. The distance between the

[1] See *Contributions from the Solar Observatory*, No. 1, *Astrophysical Journal*, March 1905.

PLATE IX

Truck for Hauling Heavy Instruments on Mount Wilson Trail

wheels was limited by the width of the trail to 24 inches (61 cm). The bed of the truck is hung by wrought-iron yokes from the running gear, the lower surface of the bed being at a height of 6 inches (15 cm) above the ground. Steering gear, of the type used on automobiles, is provided for both pairs of wheels. A man riding on the load steers the forward wheels with a hand wheel, while the rear wheels are steered with a tiller by a man walking behind the carriage. A single large horse pulls a load of a thousand pounds on this carriage without difficulty. With two horses, used in relays, the trip from the lower end of the trail to the summit and return (a total distance of about nineteen miles) is completed with such a load in less than two days (about fifteen hours on the trail). With loads not exceeding 700 pounds the round trip is completed in a single day. Up to the present time the truck has made fifty round trips, carrying all the mirrors, lenses, and heavy castings of the Snow and Bruce telescopes, the parts of a fifteen horse-power gas engine, and other heavy machines, as well as the four-inch pipe columns (some of them twelve feet long) used in constructing the steel skeleton of the telescope house (Plate XI). The lighter angle-iron and other parts of the telescope house were brought up on burros. The total weight of material carried over the trail for the present work amounts so far to about 175 tons.

As the steering and control of the carriage on the narrow mountain trail is a difficult and dangerous task, special mention should be made of the excellent work of Mr. C. O. Sparks, who has been in charge of the carriage on all of its trips. It is to the credit of Mr. Sparks that nothing has been lost or injured during transportation.

Before the heavy castings (some of them weighing as much as five tons) required for the mounting of the five-foot reflector can be taken up Mount Wilson, the trail must be widened or some other mode of transportation provided.

THE SNOW TELESCOPE

As no description of this instrument has been published, the present brief account may be prefaced by a statement regarding the construction of the telescope.

In designing the Yerkes Observatory in 1894, I provided a large

heliostat room, 12 feet (3.66 m) wide and 104 feet (31.7 m) in length.[1] A small heliostat loaned by Professor Keeler was used in this room in 1897, and it was intended to mount permanently there, mainly for spectroscopic work, a combined heliostat and cœlostat designed by Professor Wadsworth.[2] When employed as a cœlostat, a second fixed mirorr was to be used with the instrument, so as to give the desired direction to the reflected beam.[2] Some of the patterns for this instrument were made, but the pressure of other work made it necessary to postpone the construction for some time.

In 1900, after Professor Ritchey had succeeded Professor Wadsworth as superintendent of instrument construction, a cœlostat with mirror of 15 inches (38 cm) aperture was made, from Professor Ritchey's designs, for the total solar eclipse of that year. This gave such satisfactory results that the plan of constructing a large cœlostat was again taken up. Unfortunately, however, no funds were available for this purpose. In 1901, during a visit to the Observatory of Professor Cross, chairman of the Rumford Committee, I showed him the details of the instrument, as worked out by Professor Ritchey. The design called for a cœlostat of 30 inches (76 cm) aperture, with second plane mirror of 24 inches (61 cm) aperture, the latter mounted so as to slide northeast and southwest on rails lying east of the cœlostat. The concave mirror, to which the light was reflected from the second plane mirror, had a focal length of 61 feet, and a second concave mirror, of 165 feet (50.3 m) focal length, was also to be used. For this reason the heliostat room, 104 feet (31.7 m) in length, was not long enough for our purpose, and the position of its axis, in the meridian, involved loss of light. It was accordingly necessary to erect a long wooden building, on the ground south of the Yerkes Observatory.

At the kind suggestion of Professor Cross, a grant of $500 was made by the Rumford Committee in aid of an investigation to be undertaken with this telescope. Subsequently, through the kindness of Professor Pickering, chairman of the Draper Committee, two other grants, of $500 each, became available. With these funds,

[1] See "The Yerkes Observatory of the University of Chicago," Part II, *Astrophysical Journal*, **5**, 260, 1897.

[2] *Ibid.*, p. 261.

helped out by small amounts obtained from other sources, the work was begun.

An account will be published later of this cœlostat and its accessory apparatus. The long wooden house on the Observatory grounds which contained it was destroyed by fire on December 22, 1902, through the breaking down of the insulation of a high-voltage electric transmission line, which supplied the spark used for a comparison spectrum. A 24–inch plane mirror and some of the mirror supports were saved, but most of the apparatus was completely destroyed or rendered useless.

Confident that the necessary funds could be obtained from some source, I decided to construct at once a new and better instrument, and to provide for it a more suitable house. Two important changes were made in the design. In the tests of the telescope, made by Mr. Adams and myself, the definition was poor, both in the case of the Sun and the stars. I attributed this in part to the fact that the cœlostat was mounted on a pier, the surface of which was only a few inches from the ground. This led me to observe distant objects at various heights above the ground with the naked eve, with field glasses and small telescopes, and finally with the 12-inch refractor, which stands on a pier about 40 feet (12.2 m) high. I soon reached the conclusion that the cœlostat must be mounted as far as possible above the ground, and that a site shaded by low trees or bushes would be much better than unshaded soil.

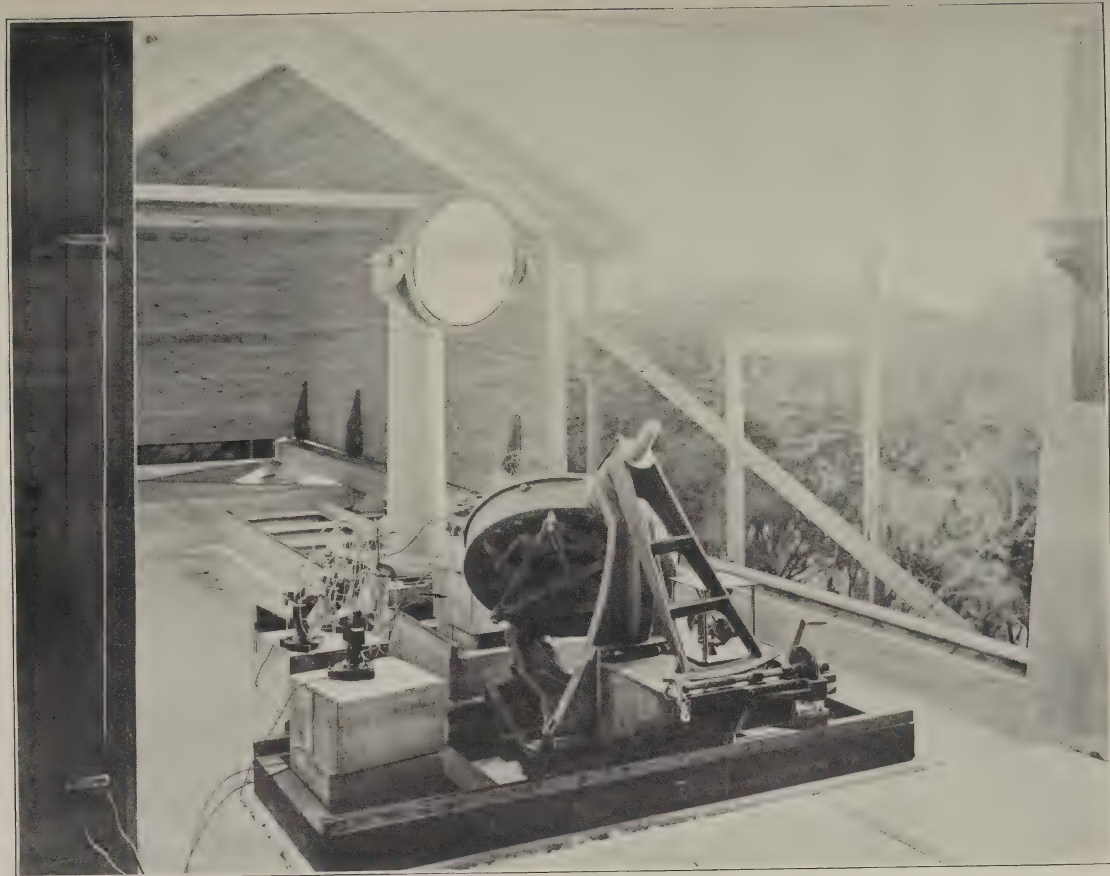
A gift of $10,000 from Miss Helen Snow, of Chicago, in memory of her father, the late George W. Snow, provided sufficient funds to complete the telescope and to instal it in a suitable house. The cœlostat was mounted on a brick pier, at a height of 15 feet (4.57 m) above the ground. In Professor Ritchey's design of the previous instrument the rays were reflected in a northeasterly direction from the cœlostat mirror to a second plane mirror, which sent them toward the southwest to one or the other of the concave mirrors. In designing the Snow telescope, a new arrangement of the second mirror was adopted by Professor Ritchey, at the suggestion of Mr. C. G. Abbot. As Plate X indicates, the light is reflected upward and to the south from the cœlostat mirror to a second plane mirror, mounted in a fork at the upper extremity of an iron column, on a carriage

which can be moved along heavy iron rails. The position of this carriage on the rails depends upon the declination of the observed object: with a low Sun the second mirror stands close to the cœlostat, but with a high Sun it must be moved away in order to intercept the reflected beam. The cœlostat itself may be moved east or west on its own rails, so that a low object near the meridian may not be hidden by the second mirror or its support.

With the exception of the solar and stellar spectroscopes, for which suitable gratings could not be obtained, the Snow telescope was practically completed in the autumn of 1903. On October 3 of that year it was formally presented to the University of Chicago by Miss Snow, in the presence of a number of guests. Dr. George S. Isham, on behalf of Miss Snow, made the presentation address. The address of acceptance was made by Dean R. S. Salisbury, of the Ogden Graduate School of Science. The manner of using the telescope was afterward demonstrated.

The tests of the telescope made at this time seemed to indicate a decided improvement in definition, which I attributed to the greater elevation of the cœlostat. The Sun's image was frequently well defined, in spite of the change of focus due to the heating of the mirrors. Of this change more will be said later. At present I wish to refer especially to the definition as affected by the design of the telescope house.

The parallel beam from the second mirror was reflected due north through a spectroscopic laboratory into a long, narrow room, at the end of which the concave mirror stood on a massive brick pier. After striking the mirror, the beam was reflected back, so as to form an image of the Sun or a star in the spectroscopic laboratory a short distance from the axis of the parallel beam. The walls and floor of the house are of wood, and the question arises whether their radiation may not heat the air in the house, and thereby affect the definition. In general, the temperature of the air within such a house must differ in some degree from that of the air outside. Hence, some effect on the definition might be expected. The warm air rising about the cœlostat, due in part to the heating of the wooden walls which surround the pier, may also cause some disturbance of the image.



The Snow Telescope when Mounted at the Yerkes Observatory

Rayleigh has shown that in a telescope tube only 12 cm long, a stratum of air in the upper part of the tube, occupying only a moderate fraction of the entire volume, would produce a sensible effect on the definition if heated 1° C.[1] In a tube 60 feet (18.3 m) long, through which the beam passes twice, the difference in temperature of a stratum, required to produce a similar effect, would be only about one three-hundredth of a degree. The assumed retardation is one-quarter of a wave, and the change of temperature from one side of the beam to the other is supposed not to be uniform.

To the practical observer such a result may seem to have little meaning. I have repeatedly seen the solar image beautifully defined with the 40-inch (102 cm) Yerkes refractor, when the air within the tube had become greatly heated—and certainly not uniformly so—after hours of continuous observation. Indeed, it is difficult to understand how such excellent definition can be obtained under these conditions. For in the optical testing-room Rayleigh's conclusions are easily verified. The great difficulty of securing a satisfactory test of a mirror by the Foucault test is well known; with a focal length as great as 145 feet (44.2 m) our opticians have waited for weeks to obtain a satisfactory test, even in the quiet air of the long testing-room in the basement of the Yerkes Observatory. The trouble resulting from stratification of the air, and the disturbance caused by the proximity to the beam of a person's hand, are familiar to all opticians. With these difficulties in mind, the problem of obtaining really good images of the Sun appears very serious. Yet the fact remains that good images are sometimes obtained. The great height of the 40-inch objective above the ground is probably an important advantage of this telescope, though the radiation of the dome on each side of the shutter-opening must produce some disturbance. The mere heating of the cell of the objective by the Sun would seem to be a sufficient cause for serious disturbance of the definition. Of course it is extremely probable that with sufficiently good atmospheric conditions all of these heating effects are actually perceptible in some degree, and that if they could be eliminated the seeing would

[1] *Collected Papers*, Vol. I, p. 434.

be much better than it is now. A skeleton tube, with a simple device for shading the cell, would probaply be advantageous.[1]

During the tests of the Snow telescope at the Yerkes Observatory, Langley's plan of stirring the air along the path of the beam was tried. The beam was made to pass through a tube of thick building paper, supported on a light wooden frame of square section, about 36 inches (91 cm) square. Electric fans were mounted at openings cut in the walls of the tube. When running at high speed, they kept the air within the tube in constant motion. At times the image of the Sun was distinctly improved in definition soon after the fans were started; but in other cases no improvement whatever resulted. It nevertheless seemed probable that a modified method of stirring the air might advantageously be employed for the Snow telescope house on Mount Wilson, and a tentative design was prepared. But further tests, made at my request by Professor Ritchey, indicated that we could not hope for satisfactory results without much more experimenting than we could afford to undertake. I accordingly abandoned this plan, and designed the cœlostat house described below.

CŒLOSTAT HOUSE ON MOUNT WILSON

In designing the new cœlostat house, I was influenced by two principal considerations:

1. The importance of placing the cœlostat as far as possible above the ground, which had been indicated by observations made with a telescope in a tree at elevations ranging from twenty to seventy feet.

2. The importance of constructing the house in such a way as to reduce to a minimum the heating and the radiation of the floor, walls, and ceiling, with the purpose of keeping the air within the house at the same temperature as the outer air.

In plan (Fig. 1), the building resembles the Snow telescope house at Williams Bay. The cœlostat stands on a carriage, which

[1] The case of the 40-inch telescope tube is doubtless hardly comparable with that of the Snow telescope house. The 40-inch tube is sealed by the objective at the upper end, and there is little mixture of the heated air of the tube with the cooler air outside. For this reason it would be interesting to close the end of the telescope house (near the cœlostat) with an objective, and try the definition under such conditions, i. e., without the concave mirror.

can be moved east or west along the rails, *a a*. On account of the configuration of the ground, which falls rapidly toward the north, it was necessary to make the long axis of the building run fifteen degrees east of north, instead of being exactly in the meridian. For the same reason this axis is not horizontal, but inclines downward five degrees toward the north. Without these modifications of the original plan, the height of the northern part of the building would have been very great, involving serious increase of expense. The rails *b b*, on which the carriage bearing the second mirror slides, are parallel to the optical axis.

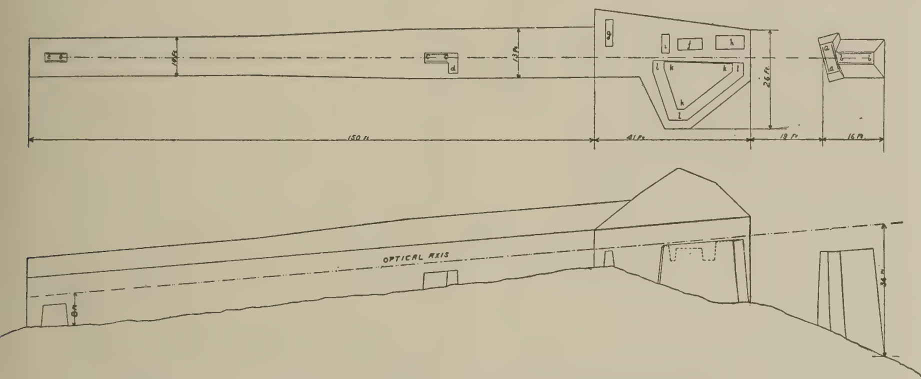


FIG. 1.—Plan and Elevation of Snow Telescope House on Mount Wilson.

Two concave mirrors, each of 24 inches (61 cm) aperture, are to be used. Of these, the mirror of 60 feet (18.3 m) focal length is mounted on its carriage so that it can be moved (for focusing), along the rails *c c*. The mirror of 145 feet (44.2 m) focal length is to be similarly mounted on the rails *e e*. When the long-focus mirror is to be used, the mirror of 60 feet focus is moved to one side, on the extension of its pier at *d*.

In designing the spectroscopic apparatus for the telescope, I have had the benefit of valuable suggestions from all members of the staff. The instruments are to be five in number, as follows:

1. A spectroheliograph with portrait lenses of 8 inches (20.3 cm) aperture, and 60 inches (152 cm) focal length, provided with four dense flint prisms. This instrument is to be carried on the pier *f*, where it will be floated in mercury (to reduce the friction of steel balls

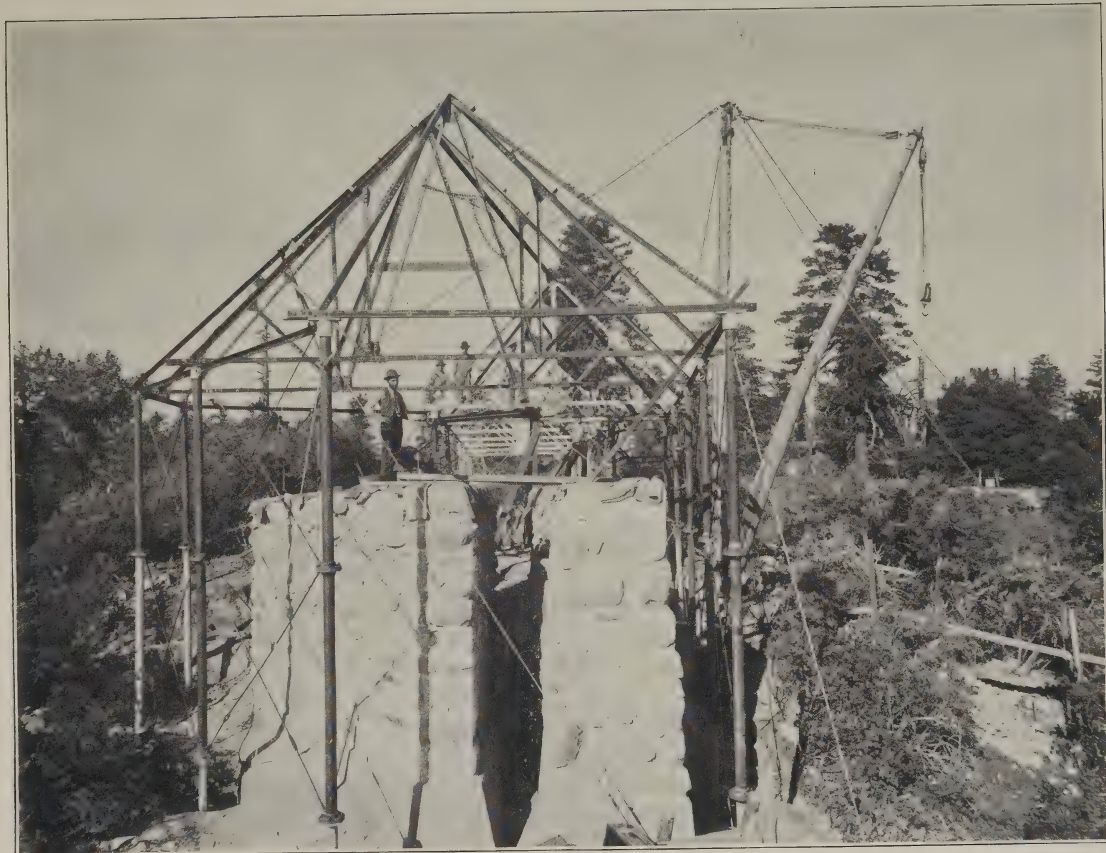
running in V rails), and moved as a whole across the 6.7 inch (17 cm) solar image given by the mirror of 60 feet focal length. The principal purpose of the instrument is to secure daily photographs of the entire solar disk with the calcium and hydrogen lines.

2. A spectroheliograph with lenses of 5 inches (12.7 cm) aperture, and 30 feet (9.14 m) focal length, provided with three light flint prisms of 50° angle. The first and second slits of this spectroheliograph are to stand on the pier *g*, while the collimator and camera lenses and the prism train will be carried by the pier *h*. The spectroheliograph will be fixed in position, and the 16-inch (41 cm) solar image given by the mirror of 145 feet focal length will be moved across the slit by a slow motion of rotation, about a vertical axis, of the 145 foot mirror. At the same time, the photographic plate will be moved synchronously across the second slit. The principal purpose of this instrument is to photograph zones about 4 inches (10 cm) wide of the large solar image, using the lines of iron and other elements which are too narrow to be employed with spectroheliographs of small dispersion. The instrument will also be employed with a plane grating, as a spectroscope for the study of the spectra of sun-spots, etc.

3. A Littrow spectrograph of 18 feet (5.49 m) focal length, with large plane grating. The single objective (on pier *h*), that serves for collimator and camera, will form an image of the spectrum just above the slit (on pier *j*). This spectrograph will be used with the 60-foot mirror, mainly for a study of the solar rotation and the spectra of sun-spots.

4. A concave grating stellar spectrograph, of about 15 feet (4.57 m) equivalent focal length, mounted on the massive pier *k k k* in the constant-temperature room *l l l*. A collimating lens of 5 inches (12.7 cm) aperture will be used with the grating, in order to avoid astigmatism. For the present, until a suitable concave grating can be obtained, a plane grating will be used with a camera lens of 5 inches aperture, and about 13 feet (3.96 m) focal length. This spectrograph is to be employed with the 60-foot mirror in an attempt to photograph, with high dispersion, the spectra of some of the brightest stars. The fixed position of the spectrograph on a massive stone pier, and the possibility of maintaining the grating at a constant temperature, should render very long exposures feasible.

PLATE XI



House for Snow Telescope on Mount Wilson
Looking North from Cœlostat Pier

5. A prism spectrograph, with collimator lens of $1\frac{1}{2}$ inches (3.8 cm) aperture and 45 inches (114.5 cm) focal length, dispersion of from one to four prisms, and camera lenses of various focal lengths, all of ultra-violet glass. The optical parts of the spectrograph will be mounted in such a way that they can be used on the large pier in the constant-temperature room, in conjunction with the slit of the concave grating spectrograph. The prism spectrograph will be used for special studies of stellar spectra, especially in the ultra-violet region.

It is to be understood that instruments 1, 2, and 3 are to be so supported, at different levels, that they will not interfere with one another, and will always be ready for use. The prism spectrograph, however, must be moved to one side when the concave grating spectrograph is to be employed.

The arrangement of the apparatus having thus been explained, let us consider more particularly the construction of the building. As Plates XI and XII show, the structure is of steel, as light as due regard for occasional high winds will permit. Steel guy ropes, anchored to large masses of concrete, afford the additional strength required in the heavy storms of winter. Since the parallel beam from the cœlostat to the concave mirror passes through a closed tube, it is not essential that this part of the building should stand high above the ground. Where the rays of the Sun fall upon the cœlostat itself, however, there can be no protection of the beam, and consequently it is desirable that the cœlostat should stand at a considerable elevation. After many tests of the seeing had been made at various points on the mountain, a site was finally selected which seemed to meet the required conditions. The cœlostat pier stands on a south slope, commanding a practically unobstructed horizon. At its south end this pier rises 29 feet (8.8 m) above the ground; hence, as the center of the second mirror is 74 inches (1.88 m) above the pier, the optical axis of the telescope is at this point about 35 feet (10.7 m) above the ground. At the north end of the pier the rising slope of the hill decreases this height to about 25 feet (7.6 m). When not in use, the cœlostat and second mirror are covered by a house on wheels, closed at both ends by double walls of heavy canvas. These may be opened, so that when the house is moved to the north, the cœlostat stands completely exposed. The movable shelter then

fits closely against the south wall of the spectroscopic laboratory, and thus forms a part of the tube through which the beam passes. When in this position the shelter has a canvas floor, so that the beam is completely protected from ascending currents after it leaves the north end of the cœlostat pier.

All parts of the building, including the movable shelter, the spectroscopic laboratory, and the long, narrow house extending north from the spectroscopic laboratory, have an inner wall and ceiling of canvas, and an outer wall composed of canvas louvres, very completety ventilated. The roof is also ventilated, by wooden louvres at the ridge, thoughout the entire length of the movable shelter and the north extension, and at the peak of the laboratory. Rain and snow are prevented from entering the roof louvres by means of canvas curtains, which can be raised or lowered at will. The house extending north from the laboratory has a floor of canvas, with an air-space below, through which the air may pass freely.

In traversing the spectroscopic laboratory, the beam necessarily passes very close to the wall of the constant-temperature room. To diminish the effect of radiation from this wall, a covering of sheet metal is arranged so that a constant current of air may be drawn between the sheet metal and the wall by means of an exhaust fan. Outer air is brought in from the west side of the laboratory, and no internal drafts are created, as the connections between the air-space and the supply and exhaust tubes are perfectly tight. It is hoped that any evil effects of radiation from the stone piers and the wooden floor of the spectroscopic laboratory can be eliminated by similar devices.

The louvres surrounding the cœlostat pier are intended to protect the pier from vibration caused by the wind, and from heating by the Sun. The steel structure does not touch the pier at any point, and is therefore made rigid enough to support itself in high winds.

The cœlostat, and the supports for the plane mirror and the 60-foot concave mirror, are now in place on the piers, but heavy storms have prevented the mirrors from being mounted. The concave grating stellar spectrograph is nearly ready to be set up, and work is well advanced on the smaller of the two spectroheliographs. The ultra-violet glass prisms and lenses for the stellar spectrograph have been

PLATE XII

House for Snow Telescope on Mount Wilson
Showing Cœlostat Pier and Movable Shutter

completed by the Carl Zeiss Company, and orders have been placed for the optical parts of the 30-foot spectroheliograph and the Littrow spectrograph. Through the courtesy of the president and trustees of the University of Chicago, the Snow telescope and some of its accessories will be used by the Solar Observatory for some time. It will subsequently be replaced by a similar telescope constructed in our own instrument shop.

THE HOOKER EXPEDITION

As the result of a gift of $1,000, made by Mr. John D. Hooker, of Los Angeles, the Bruce photographic telescope of the Yerkes Observatory has been brought to Mount Wilson by Professor Barnard, for use during a period of several months, after which it will be returned to Williams Bay. A full description of this telescope has recently been published by Professor Barnard in the *Astrophysical Journal.*[1] The house built for the Bruce telescope on Mount Wilson has a sliding roof, which leaves the entire sky free when it is pushed back. Professor Barnard has already obtained some excellent photographs of *Orion* and other constellations. Their quality is such as to give promise of important results, as soon as the stormy weather of the rainy season abates sufficiently to permit long exposures to be given.

THE "MONASTERY"

In the original estimates for the Solar Observatory, made by the committee of the Carnegie Institution, $52,500 was set apart for the construction of dwelling houses on Mount Wilson for the families of the staff, and $51,000 for a large building, containing offices for all the members of the staff, and rooms for laboratories and instrument shops. In these particulars the report simply adopted the plan followed by the Lick and Yerkes Observatories. A residence of six months in a log cabin on Mount Wilson, under conditions which rendered necessary the greatest economy of expenditure, convinced me that a better use could be made of the Institution's funds. In the first place, it is by no means desirable to confine families, and especially children deserving every educational advantage, within the narrow limits of an isolated observatory colony. Furthermore,

[1] 21, 35–48, 1905.

the work of an instrument shop, and much routine computing as well, can be done at much less expense and to better advantage in a town, where foundries and various sources of supply are at hand, and better workmen and computers can be employed. Finally, a great economy can be effected by using funds for instruments, machinery, and books—the tools of the investigator—that would otherwise be spent for mere buildings. In short, I believe the principle should be recognized that the mountain site is valuable for *observations*, and that most other classes of work can be better done elsewhere. These considerations strike one most forcibly in a place where the cost of building materials is doubled by transportation over the trail.

The isolation of most mountain sites, however, might seem to demand that the staff of such an observatory should be composed only of celibates, or that its members must be content to experience long periods of separation from their families. In this particular Mount Wilson is most fortunately situated. The city of Pasadena, which is hardly to be surpassed as a place of residence, lies at the very foot of the mountain, and can easily be reached in two and one-half hours. Los Angeles, with its large machine shops, foundries, and supply houses, is also near at hand. It is thus perfectly feasible to have the families of the observers live in Pasadena, where members of the staff can spend Sundays, and go on business at other times. We are following this plan, and find it is as satisfactory as could be expected under the circumstances.

I consider it very desirable that each member of an observatory staff, if engaged in work requiring concentrated attention, such as computing or measuring, should have a workroom of his own. The space occupied may be very small, but it should certainly be set apart for individual use. This requirement, together with the necessity of supplying living accommodations for the astronomers, determined the design of the "Monastery."

As shown in plan in Fig. 2, the building has two wings; one containing the dining-room, kitchen, pantries, two bedrooms, wood-shed, etc.; the other, the bedrooms and offices of the astronomers, guest-room, bathroom, etc., opening on a long, narrow hall. Each astronomer has a small bedroom and an adjoining office. The

convenience of this arrangement, and the satisfaction it has given to all the members of the staff, indicate that a great saving in expense, without loss of efficiency, will be effected. The large room, with stone fireplace, which unites the two wings, serves as a general library. The "Monastery" stands at the extreme end of a narrow point with precipitous walls, and commands a fine view of the neighboring mountains, the San Gabriel Valley, the cities of Pasadena and Los Angeles, and the Pacific Ocean. It was designed, after our plans, by Messrs. Hunt & Gray, architects.

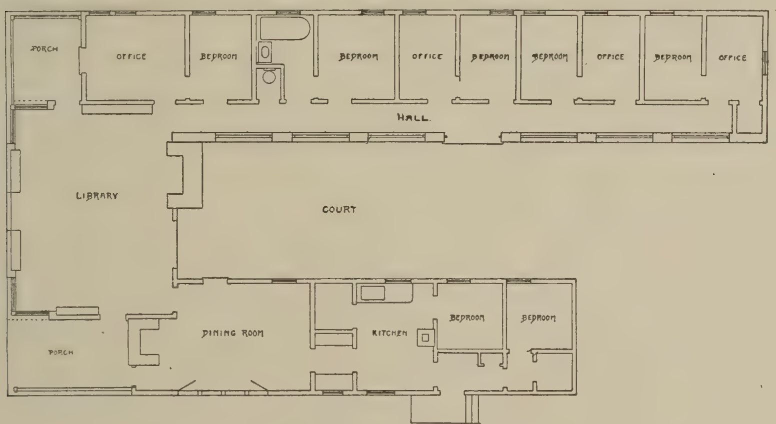


FIG. 2.—Plan of the "Monastery."

Through a recent gift from Mr. John D. Hooker, a small guest-house, containing two bedrooms and a living-room, will soon be erected near the Monastery.

POWER HOUSE AND REPAIR SHOP

A one-story building, 15 × 35 feet (4.57 × 10.67 m), situated between the Snow telescope and the "Monastery," is equipped as a small power-house and repair shop. It contains a 15 horse-power Witte gasoline engine; 7½ K. W. dynamo, giving either alternating or direct current; storage battery of thirty cells, small screw-cutting lathe; Rivett milling machine; sensitive drill; emery grinder; Oliver trimmer; forge and anvil; and a good assortment of small tools needed for repairs and for a certain amount of construction work.

Although our large instrument shop in Pasadena is prepared to undertake any class of work, I regard a small shop on the mountain as indispensable. The engine, dynamo, and storage battery furnish current for arc and spark discharges, and for temperature control required in spectroscopic work, power to run the spectroheliographs, exhaust fan, etc., and light for the offices and laboratories.

A line for transmitting electric power from the San Gabriel Valley will be installed later, since much more power will be required for the 5-foot reflector and other purposes. The present power plant was provided before it was known that a large Solar Observatory would be established by the Carnegie Institution.

It was originally intended to supply water to the various buildings from a well at Strain's Camp, about 325 feet (99 m) below the summit of Mount Wilson; but as the well yielded almost no water last autumn (after an unusually dry period), it is likely that a more reliable source will be chosen.

GENERAL LABORATORY

A small laboratory building, probably of fire-proof construction, will be erected near the Snow telescope in the spring. This will contain a large grating spectrograph, with various accessory apparatus, such as a Du Bois half-ring electromagnet for the Zeeman effect, an arc in pressure chamber, a transformer and condenser for studies of spark discharges, etc. The equipment will also include a Pulfrich stereocomparator, principally for the study of spectroheliograph plates; an Abbe spectrometer; an interferometer, for the measurement of absolute wave-lengths; measuring machines for spectra and for stellar photographs; globe for the measurement of heliographic positions, etc. In addition to the spectroscopic laboratory, the building will contain a small chemical laboratory, an enlarging room, photographic dark-rooms, rooms for the storage of negatives, etc. A visible recording variometer and magnetic storm detector will be established in a separate building, for use in connection with the solar observations.

PASADENA OFFICES AND LABORATORIES

With the invaluable assistance of the Pasadena Board of Trade, a piece of land, on Santa Barbara Street, 150 feet (45.7 m) front by

208 feet (61 m) deep, has been secured for the Pasadena offices and instrument shop. The building, which is now under construction, was designed by Professor Ritchey. It is 50×100 feet (15.2×30.5 m) in size, with an optical testing-room, 150 feet (45.7 m) long, extending 68 feet (20.7 m) beyond it in the rear. The walls are of brick, and the floor of cement. Pains will be taken to make the structure throughout as nearly fire-proof as the available funds will permit, since the optical and mechanical parts of instruments under construction will be very valuable.

The building will contain offices for Professor Ritchey and myself, and a stenographer; drafting-room, machine shop, instrument shop, pattern shop, lacquering-room, constant-temperature room, room for 5-foot (1.5 m) grinding machine, room for 40-inch (1 m) grinding machine, long optical testing-room, photographic dark-rooms, enlarging-room, etc. The equipment includes a No. 2 Brown & Sharpe Universal milling machine, 24×24-inch (61×61 cm) Gray planer, 20-inch (51 cm) Hendey-Norton engine lathe, 12-inch (30.5 cm) Hendey-Norton tool maker's lathe, No. 4 Rivett bench lathe, No. 2 Landis Universal grinding machine, drill press, pattern-maker's lathe, circular saw, band-saw, Oliver trimmer, automatic hack-saw, emery grinder, etc. The supply of small tools is very complete. The optical laboratory will contain all necessary machinery for grinding, polishing, and testing mirrors, with apertures as great as 5 feet (1.5 m), and focal lengths as great as 150 feet (45.7 m).

Most of the above machine tools are now in use at the instrument shop temporarily occupied in the Seward Building, between Colorado and Union Streets. At present, two draftsmen, one instrument-maker, three machinists, and two pattern-makers are at work there, under the direction of Professor Ritchey. No optical work can be done until the new shop is completed.

It is probable that offices for a staff of computers will ultimately be provided adjoining the instrument shop.

EXPERIMENTS WITH FUSED QUARTZ

As already stated, glass mirrors are subject to change of figure when exposed to the Sun's rays. At the independent suggestion of Dr. Billings and Dr. Elihu Thomson, experiments have been undertaken with the object of using fused quartz instead of glass for the

mirrors, since its coefficient of expansion is only about one-tenth as great. The work has been done by Professor Ritchey and Mr. Wingren, with the aid of a grant given last spring for this purpose by the Carnegie Institution. The quartz is easily fused in an electric furnace, but the fused mass is filled with fine bubbles, which increase in number and size as the temperature of the furnace is increased. An attempt is being made to eliminate the bubbles, in order to secure fused quartz for prisms and lenses. For mirrors, as Professor Ritchey suggests, blocks like those already obtained will probably serve very well, if the bubbles at one surface can be gotten out by remelting with the flame of an electric arc.

STAFF

The staff of the Solar Observatory is at present constituted as follows:

George E. Hale, Director.

G. W. Ritchey, Astronomer, and Superintendent of Instrument Construction.

Ferdinand Ellerman, Assistant Astronomer.

Walter S. Adams, Assistant Astronomer.

There is a post-office on Mount Wilson, about a mile from the Observatory, but the delivery of mail is so infrequent and irregular, that I conduct my correspondence from the Observatory Office in Pasadena, where letters for me should be addressed. Letters and printed matter for Professor Ritchey should be sent to the same address, but printed matter intended for me should be addressed to Mount Wilson, Cal., as my scientific library is at the Observatory. Printed matter for the Solar Observatory, and both letters and printed matter for Mr. Ellerman and Mr. Adams, should be addressed to Mount Wilson.

Books and papers, especially on astrophysical subjects, will be gladly received for the library of the Solar Observatory. Sets of observatory publications, which are greatly needed, may be forwarded from abroad, free of expense, through the International Bureau of Exchanges of the Smithsonian Institution, which has offices in the principal cities of Europe. It is hoped that some return for such contributions may ultimately be made in the form of our own publications.

Mount Wilson, Cal.,
February 8, 1905.

INTENSITY OF GRATING SPECTRA

By R. W. WOOD

Having had occasion recently to plan for the construction of a short-focus spectrograph of fairly large dispersion in the visible region, the question of gratings *versus* prisms came up. Plenty of data regarding prisms are to be found in Kayser's new treatise in spectroscopy, but little or nothing seems to have been published regarding gratings, the only statements made being rough guesses. It seemed worth while to make a study of the distribution of the light (monochromatic) in the different spectra of a typical grating.

The apparatus which my assistant Mr. Pfund arranged for making the measurements was very simple, and the whole thing was accomplished in half an hour. The grating selected was a fairly typical one, the central image rather dark and of a brownish color, indicating that no very marked selective action for certain colors was present, and the first-order spectrum on one side extremely bright. The measuring apparatus, or photometer, consisted of a pair of Nicol prisms (one mounted in a graduated circle), a small piece of silvered glass, and a bright and uniform sodium flame. The silvered glass can be made by dissolving the varnish from the back of a piece of modern mirror, and polishing with rouge. It is mounted vertically at an angle of 45° with the axes of the nicols, and covers the lower half of the field (Fig. 1). The soda flame is immediately behind the polarizing prism, and the grating stands to one side, as shown in the figure. By turning the grating the central, or any one of the lateral

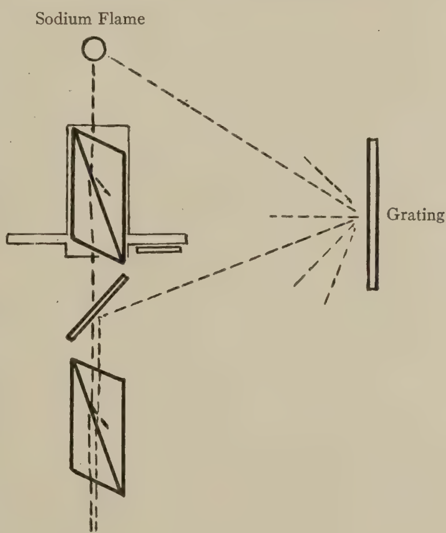


Fig. 1.

(spectral), images of the flame can be viewed in the silvered mirror immediately in contact with the image of the flame seen through the nicols, and by turning one of them the intensities can be accurately adjusted. We first set the graduated nicol in the zero position, and then turn the other nicol to the position of extinction. The intensity of the restored light for a given angle measured from this position is proportional to the square of the sine of the angle. The central image can be located easily by watching for the reflection of the flame in the unruled portion of the surface. The results obtained are recorded in the following table, eight spectral images being measured:

Fourth Spectrum	Third Spectrum	Second Spectrum	First Spectrum	Central Image	First Spectrum	Second Spectrum	Third Spectrum	Fourth Spectrum
0.073	0.057	0.20	0.31	0.16	0.98	0.096	0.032	0.01

The numbers given are the squares of the sines of the angles, and represent the intensities of the images as fractional parts of the light transmitted through the first nicol. The intensity of the first spectrum on the right is as great as the sum of all the others together with the central image (0.94), which amounts to saying that half of the total light reflected is found in one spectrum.

It is frequently stated that a nicol reduces the intensity of unpolarized light by one-half. The reduction is obviously greater than this on account of the reflections at the two oblique surfaces, and to a slight extent by the balsam film. In the present case the surfaces of the prism were slightly dull, and I doubt if the intensity of the transmitted light was much over 40 per cent. of the original intensity. Calling the intensity of the soda flame 100, we get the intensities of the spectra by multiplying 40 by the fractions given in the table. The sum of these intensities (eight spectra and central image) is 75.6, which agrees fairly well with Rubens' determination of the reflecting power of spectrum metal for yellow (70 per cent.). This indicates that the ruling of the surface interferes in no way with the *total* reflection, which is what might be expected. The interesting point is that half of the total light is found in one spectrum. If speculum reflects 70 per cent., this means that we have 35 per cent. of the light in the first-order spectrum, or about one-third of the original amount.

To determine whether or not this was the case, I arranged a photographic lens, soda flame, and the grating in such a way that the lens pictured the *direct* image of the flame and the first-order spectral image side by side on a photographic plate (Fig. 2). A ray filter of aurantia was placed in front of the plate, to eliminate the action of the blue and green rays from the Bunsen flame, which would be present in the direct image, and absent in the spectral image. The spectral image was exposed thirty seconds, and the direct ten, and on developing it was found that the images had almost exactly the same intensity, showing that no error of any considerable amount had been made in the photometric work. Of course, the same intensity distribution might not, and probably would not, be found

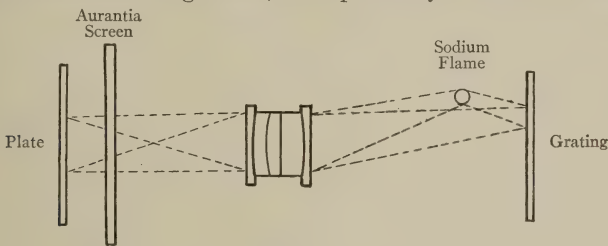


FIG. 2.

for other colors, but the results obtained with sodium light give a fair idea of what may be expected of an average grating.

The difficulty of ruling satisfactory gratings of very short focus (one meter or less), combined with the fact that only short lines can be ruled, makes it appear probable that for work of certain kinds better results can be expected with large plane gratings combined with achromatic lenses. Two flint prisms of 60° would give us about the same average dispersion, and the intensity would be a little more than double that given by the grating, since two prisms of this description transmit 75 per cent. of the light, according to Pickering's table given in Kayser's *Handbook*. The measurements which I have recorded were made merely for my own information, without any idea of publication. As they may prove of some interest to others, it has seemed worth while to put them on record. I have, of course, said nothing about resolving powers in considering the two types of dispersion pieces.

JOHNS HOPKINS UNIVERSITY,
January 8, 1905.

THE VARIABLE RADIAL VELOCITY OF *SIRIUS*

By W. W. CAMPBELL

The increasing number of binary stars, of relatively short period, whose internal motions can be observed by both micrometric and spectrographic methods, requires that radial-velocity observers should deal somewhat extensively with double-star orbits. This subject, naturally simple, is unfortunately complicated by the use of a great many heterogeneous systems and nomenclatures to define the orbital elements. Before proceeding to discuss one of the stars of the class described, it seemed desirable to formulate, if possible, a simple system and nomenclature of double-star elements which should meet all the requirements in that department of astronomy, which would readily adapt themselves to the evidence of the spectrograph as to the inclination of the orbital plane, and which should follow as closely as possible the methods and notation of cometary orbits. The following system is respectfully submitted. In giving it final form, Messrs. Hussey and Aitken, who have been especially interested in this subject, made several suggestions which have been incorporated. For the convenience of spectrographic and micrometric observers, the system is published both here and in Dr. Aitken's paper (*L. O. Bulletin* No. 71).

Let

P=the period of revolution, in mean solar years.

The elements P, T, e, and a have their usual significance. The elements ☊ and ω have the significance attached to ☊ and λ ($=\pi-$ ☊), respectively, by Burnham, See, Hussey, Aitken, and others.

T=the Greenwich mean time of periastron passage.

e=the eccentricity.

a=the major semi-axis of the orbit, in seconds of arc.

☊ =the position angle of that nodal point which lies between position angles 0° and 180°; that is, the position angle of the line of intersection of the orbit plane with the plane at right angles to the line of sight.

ω = the angular distance of periastron from the nodal point (☊), measured along the orbit in the direction of the secondary's motion from 0° up to 360°. It should be stated whether the position angles are increasing or decreasing.[1]

i = the inclination of the orbit plane; that is, the angle between the plane at right angles to the line of sight and the orbit plane. Its value lies between 0° and ± 90°. i is positive, that is, between 0° and +90°, when the orbital motion at the nodal point (☊) is away from the observer; and i is negative, that is, between 0° and −90°, when the orbital motion at the nodal point (☊) is toward the observer.[2]

μ = the mean daily motion of the companion measured in the direction of motion.[3]

There is apparently no simple system of defining the elements of stellar orbits which will apply equally well to both visual and spectroscopic orbits. The difficulty lies in the following facts. The computer of the visual orbit must publish his elements with the quadrant of i left unknown: and the computer of the spectrographic orbit must publish his elements with the value of i completely unknown. In the former case the micrometer leaves the position angle of the ascending node and the distance from the ascending node to the periastron both uncertain by 180°; the spectrograph determines which is the ascending node, but to change the visual elements ☊ and ω by 180° would introduce confusion. It is preferable simply to retain

[1] The direction of the motion being described in the elements, it becomes possible to construct the orbit from the elements alone, and without recourse to the observations.

[2] The inclination determined from micrometer measures alone should always carry the double sign ± (plus *or* minus), for the sign of the inclination is indeterminate. As soon as relative radial velocities have been measured with the spectrograph, only one sign of i need be retained; and no other change in the elements will be required in order to define the orbit completely.

[3] The formulæ used in computing the apparent position angle θ and the apparent distance ρ at the time t, from the elements given on this system are

$$M = \mu\,(t-T) = E - e \sin E$$

$$r = a\,(1 - e \cos E)$$

$$\tan\frac{v}{2} = \sqrt{\frac{1+e}{1-e}}\,\tan\frac{E}{2}$$

$$\tan(\theta - \Omega) = \pm \tan(v+\omega) \cos i \quad \left[\pm \text{ according as position angles are } \begin{matrix}\text{increasing}\\ \text{decreasing}\end{matrix}\right]$$

$$\rho = r\,\frac{\cos(v+\omega)}{\cos(\theta - \Omega)}\,.$$

In the case of increasing position angles, $\theta - \Omega$ and $v+\omega$ are in the same quadrant; but in the case of decreasing position angles they are in different quadrants.

the correct sign of i and drop the incorrect one. In the spectrographic orbit, the observations determine the longitude of periastron (ω) measured from the ascending node. In a determination of the elements of the same orbit micrometrically, the value of ω may differ 180° from the spectrographic ω. To equalize them by changing the spectrographic system of nomenclature would likewise introduce confusion. It seems wise to use the double star system of nomenclature described above in dealing with visual orbits, and the nomenclature of Lehmann-Filhés' method[1] of determining spectrographic orbits in the other case. Transformation from one system to the other will be easy for any given orbit determined from the two classes of observations.

The parallax and the elements of the orbits of the binary star *Sirius* are probably more accurately determined than in the case of any other double star, with the possible exception of *a Centauri*. Zwiers' elements on the above system are:[2]

$$P = 48.8421 \text{ years}$$
$$T = 1894.0900$$
$$a = 7''.594$$
$$e = 0.5875$$
$$\Omega = 44° \; 30'.2 \; (1900.0)$$
$$\omega = 147 \; 53.6, \text{ position angles decreasing}$$
$$i = \pm 46° \; 1'.9$$
$$\mu = 7°.37069$$

The weighted mean value of the Cape of Good Hope determinations of the parallax is 0″.37.[3] Auwer's[4] result for the relative masses of *Sirius* and its companion is 2.20 : 1.04.

Lehmann-Filhes[5] has developed a very convenient formula for determining the radial velocity of a star due to its orbital motion. If we let the radial velocity V be expressed in kilometers per second, a in seconds of arc, P in mean solar years, π'' the star's parallax in seconds of arc, 149,500,000 the mean distance of the Sun in kilometers corresponding to a solar parallax of 8″.80, then

[1] *Astronomische Nachrichten*, **136**, 16, 1894.

[2] *Proceedings of the Amsterdam Academy of Sciences*, May 27, 1899.

[3] Sir David Gill, *Monthly Notices, R. A. S.*, **58**, 81, 1898.

[4] *Astronomische Nachrichten*, **129**, 232, 1892.

[5] *Ibid.*, **136**, 19, 1894, Equation (2).

$$V = \frac{149{,}500{,}000\, a \cdot 2\pi \sin i}{365.25 \cdot 86{,}400\, \pi'' P\sqrt{1-e^2}} [e \cos \omega + \cos (v+\omega)] \ ,$$

or,

$$V = [1^*47372] \frac{a \sin i}{\pi'' P\sqrt{1-e^2}} [e \cos \omega + \cos (v+\omega)] \ .$$

In the spectrographically-determined orbit, i is always plus, for the deduced value of ω is measured from the ascending node. Care must be taken to distinguish between the motions of the companion with reference to the primary, and of the primary and secondary with reference to the center of mass of the system.

The value of V for the companion of *Sirius* with reference to the primary becomes

$$V = \mp 5.536 \pm 11.125 \cos (v + 147^\circ\ 53'.6) \ .$$

It will appear in the sequel, from the observations with the Mills spectrograph, that i (in the visual orbit) is plus. Therefore the radial velocities of the companion with reference to the primary are given by

$$V = -5.536 + 11.125 \cos (v + 147^\circ\ 53'.6) \ .$$

It follows, from Auwer's values of the relative masses, that the radial velocities of the secondary with reference to the center of mass of the system are given by

$$V_2 = \frac{2.20}{3.24} [-5.536 + 11.125 \cos (v + 147^\circ\ 53'.6)] \ ,$$

$$V_2 = -3.759 + 7.554 \cos (v + 147^\circ\ 53'.6) \ ;$$

and the radial velocities of the primary with reference to the center of mass of the system are given by

$$V_1 = -\frac{1.04}{3.24} [-5.536 + 11.125 \cos (v + 147^\circ\ 53'.6)] \ ,$$

$$V_1 = +1.777 - 3.571 \cos (v + 147^\circ\ 53'.6) \ .$$

The values of V, V_2, and V_1 are tabulated for the convenience of other observers at intervals of one year throughout the period of a revolution, working each way from $T = 1894.0900$, to the time of apastron passage, 1918.5110. The maximum relative velocities of approach and recession occur at the two nodal points, and the extreme range of the primary's speed is the arithmetical sum of these maxima, or $5.35 + 1.79 = 7.14$ km.

* Logarithm of factor constant for all orbits.

	V	V_2	V_1		V	V_2	V_1
1870.09	+3.99	+2.71	−1.28	1894.09	−14.97	−10.16	+4.81
71.09	4.21	2.86	1.35	95.09	16.66	11.31	5.35
72.09	4.42	3.00	1.42	96.09	15.32	10.40	4.92
73.09	4.63	3.15	1.48	97.09	12.96	8.79	4.17
74.09	4.82	3.27	1.55	98.09	10.63	7.21	3.42
75.09	4.99	3.38	1.61	99.09	8.65	5.87	2.78
76.09	5.14	3.49	1.65	1900.09	6.98	4.74	2.24
77.09	5.28	3.58	1.70	01.09	5.59	3.79	1.80
78.09	5.40	3.66	1.74	02.09	4.40	2.99	1.41
79.09	5.49	3.72	1.77	03.09	3.38	2.30	1.08
80.09	5.56	3.77	1.79	04.09	2.50	1.70	0.80
81.09	5.59	3.79	1.79	05.09	1.71	1.16	0.55
82.09	5.59	3.79	1.79	06.09	1.02	0.69	0.33
83.09	5.54	3.76	1.78	07.09	−0.41	−0.28	+0.13
84.09	5.43	3.68	1.75	08.09	+0.41	+0.10	−0.04
85.09	5.24	3.55	1.69	09.09	0.65	0.44	0.21
86.09	4.93	3.34	1.59	10.09	1.11	0.75	0.36
87.09	4.47	3.04	1.43	11.09	1.54	1.05	0.49
88.09	3.77	2.56	1.21	12.09	1.94	1.32	0.62
89.09	2.74	1.86	0.88	13.09	2.30	1.56	0.74
90.09	+1.15	+0.78	−0.37	14.09	2.64	1.80	0.84
91.09	−1.29	−0.88	+0.41	15.09	2.95	2.01	0.94
92.09	5.02	3.41	1.61	16.09	3.25	2.21	1.04
93.09	10.13	6.87	3.26	17.09	3.53	2.40	1.13
94.09	−14.97	−10.16	+4.81	18.09	3.78	2.57	1.21
				1918.511	+3.86	+2.62	−1.24

The foregoing computations were made, for the most part, shortly after the publication of Zwiers' orbit. Doberck has recently computed an orbit[1] of *Sirius*, using observations up to 1903.16. However, his elements differ very little from Zwiers', and the two orbits give substantially the same radial velocities. The computed total range in the primary's radial velocity from Doberck's orbit is 6.61 km, as against 7.14 km from Zwiers' orbit.

Thirty-one spectrograms of the bright component of *Sirius* have been obtained with the Mills spectrograph since the year 1896. Mr. Burns has recently made definitive measures of all of them, and his results are given below. The negatives of 1896 and 1897 were obtained with the original imperfect camera lens referred to in the published description[2] of the spectrograph. The field of good definition for this lens was a point, and the field of moderately good definition was very small. In the Sirian type of spectrum there were therefore very few lines suitable for safe measurement, and the

[1] *Astronomische Nachrichten*, **166**, 321–326, 1904.

[2] *Astrophysical Journal*, **8**, 132–134, 1898.

results have smaller weight than those secured later with more perfect lenses. The lines in this type of spectrum are rendered difficult of measurement both by underexposure and by overexposure, and that exposure time which gives the proper density should be determined by experiment. This has not been practicable in the present series of observations, as they were obtained under a great variety of conditions, for the most part incident to the experimental development of the subject; with five different camera lenses having three quite different focal lengths; without and with a correcting lens in front of the slit; with straight and curved slits; with two different spectrographs; on slow, medium, and quick plates; under various atmospheric conditions; and by several observers. The correct exposure time for this brilliant star is very short; and, in the observer's solicitude to distribute the light uniformly along the slit, the negatives were overexposed in many cases. All the spectrograms are included in the following list; none have been rejected. The accordance of the results for any given epoch could easily be improved by making the series of observations under uniform conditions and with properly timed exposures.

Neglecting the plate of 1898.07, which is very poor and stands alone, there is an unmistakable progression in the results, which we attribute to the effect of orbital motion. Whether the irregularities in the progression are real, and due to unrecognized disturbing forces in the system, or are purely accidental, cannot now be stated; but they should be examined in connection with future series of observations.

The observed progression is in the direction of algebraically decreasing velocities, and this determines that the positive value of the inclination i is to be used.

The observed velocity should equal the computed orbital velocity plus the velocity of the center of mass of the system. If we let V_m represent the velocity of the center of mass, then each observation supplies an equation of the form

$$V_m = V_{\text{observed}} - V_1 \ .$$

Combining the thirty-one equations, we obtain as the velocity of the system of *Sirius*,

$$V_m = -7.36 \text{ km per second} \ .$$

Date	Velocity	Remarks
1896, October 2........	−1.4 km	Overexposed
October 2........	−1.0	Slightly overexposed
October 3.......	−1.6	Badly overexposed
1897, January 5........	−3.6	Lantern-slide plate
January 21...... ..	−4.3	
February 22........	−5.6	
February 23........	−5.3	Underexposed, lantern-slide plate
February 24........	−3.2	Lantern-slide plate
Mean 1896.97, 8 plates.....	−3.2 km	
1898.07, 1 plate.......	−5.9 km	Badly overexposed
1898, September 19.......	−3.8	32-inch camera, comparison poor
September 22.......	−5.0	Comparison incomplete on one side
September 28.......	−3.7	Seed 23 plate
October 9.......	−2.1	Seed 23 plate, comparison poor on one side
Mean 1898.74. 4 plates....	−3.6 km	
1899, September 26.......	−5.0	
October 23.......	−4.2	32-inch camera
October 23.......	−3.3	32-inch camera
October 23.......	−4.3	32-inch camera
1900, February 14.......	−5.7	32-inch camera
March 20.......	−5.6	32-inch camera
Mean 1899.92, 6 plates. ..	−4.8 km	
1901.93, 1 plate	−4.8 km	
1902, December 1.......	−6.6	Star poor, comparison very poor
December 17.......	−7.4	
December 22.......	−7.0	Poor plate
1903, February 10.......	−6.2	
February 10.......	−5.8	Comparison poor on one side
February 10.......	−7.2	Comparison poor
February 15.......	−7.3	Overexposed, focus poor
February 23.......	−6.5	Overexposed
February 23.......	−7.8	Focus rather poor
Mean 1903.07, 9 plates....	−6.9 km	
1904, December 13.......	−5.6	Overexposed
December 13.......	−5.2	
Mean, 1904.95, 2 plates...	−5.4 km	
1905, February 13*.......	−7.8	Overexposed
February 13.........	−7.0	Overexposed
Mean, 1905.12, 2 plates...	−7.4 km	

* Added while passing through the press.

Spectrographic observations of *Sirius* have been made, and published, by Vogel and Scheiner[1] at Potsdam, by Deslandres[2] at Paris, and by Adams[3] at the Yerkes Observatory.

Vogel and Scheiner secured ten spectrograms from 1888 to 1891. Their results were quite accordant, but they are not in harmony with the velocities required by the recent elements of *Sirius'* visual orbit and the value $V_m = -7.36$, just determined.

Deslandres' 1891 observation lies on the opposite side of these requirements, but his 1895 observation lies on the same side and near to them.

Adams' excellent series of ten observations obtained from December 1901 to March 1902 is in good agreement with the Mount Hamilton results. However, the combination of their results with the Potsdam velocity for 1890.09 could not be expected to give a value of the parallax approximating to Gill's value, as the computed difference in the velocities at the two epochs is only 1.79 kilometers.

The following table contains all the published observations known to me, combined into groups, those forming each group covering only a short interval of time. The number of observations in each group

Observations Made at	Date	No. of Observations Combined	Observed Velocity	V_1	V_1+V_m
Potsdam.....	1888.99	3	−13.9 km	−0.92 km	−8.3 km
Potsdam.....	1890.09	3	−17.0	−0.37	−7.7
Paris........	1891.17	1	−1.2	+0.49	−6.9
Potsdam.....	1891.20	4	−14.9	+0.52	−6.8
Paris........	1895.21	1	−4.1	+5.30	−2.1
Lick.........	1896.97	8	−3.2	+4.26	−3.1
Lick.........	1898.07	1	[−5.9]	+3.43	−3.9
Lick.........	1898.74	4	−3.6	+2.99	−4.4
Lick.........	1899.92	6	−4.8	+2.33	−5.0
Lick.........	1901.93	1	−4.8	+1.47	−5.9
Yerkes.......	1902.06	10	−6.9	+1.42	−5.9
Lick.........	1903.07	9	−6.9	+1.09	−6.3
Lick.........	1904.95	2	−5.4	+0.58	−6.8
Lick.........	1905.12	2	−7.4	+0.54	−6.9

[1] *Publicationen des Astrophysikalischen Observatoriums*, **7** (I), 97, 101, 1892; also *Astronomy and Astro-Physics*, **11**, 151–57, 1892.

[2] *Comptes Rendus*, **113**, 739, 1891; also *Spécimens de photographies astronomiques*, Paris, 1897.

[3] *Astrophysical Journat*, **15**, 215, 1902.

is indicated in column three. The computed relative orbital velocity, V_1, of the primary is given in column 5. The last column contains the corresponding values of

$$V_1+V_m=V_1-7.4\text{ km} .$$

Lick Observatory,
University of California,
January 25, 1905.

A LIST OF NINE STARS WHOSE RADIAL VELOCITIES VARY

By W. W. CAMPBELL and HEBER D. CURTIS

The following nine spectroscopic binary stars discovered from observations made with the Mills spectrograph are additional to the forty-eight[1] already announced. Some of the stars on the present list have been suspected of variability for several years, and two of the stars, *α Andromedae* and *τ Sagittarii,* were definitely known to be binary here in advance of their prior announcement by other observers.

Measures given to tenths of a kilometer are definitive, and those to the nearest kilometer are preliminary and approximate unless otherwise stated.

α Andromedae ($\alpha = 0^h\ 3^m$; $\delta = +28°\ 33'$)

This star is of Type A, with a good magnesium line at λ 4481. It was announced as a binary by Slipher in *Lowell Observatory Bulletin* No. 11.

The Lick Observatory measures are as follows:

Date	Velocity	Observer
1901, August 13............	−18km	Reese
	−17	Campbell
1903, September 22.........	−26	Curtis
September 27.........	− 8	Curtis
	−10	Brasch[2]
October 5............	− 2	Brasch
October 12...	− 6	Curtis
	− 4	Brasch
November 30.........	−36	Curtis
	−35	Brasch
December 21.........	−28	Moore[2]
	−26	Brasch

The binary character of this star was discovered from the third plate by Dr. H. D. Curtis.

ζ Ceti ($\alpha = 1^h\ 46^m.5$; $\delta = -10°\ 50'$)

[1] This does not include the five binaries announced by Wright in *Bulletin* No. 60, discovered by the D. O. Mills Expedition to Chile; nor the variable stars W *Sagittarii,* Y *Sagittarii,* and S *Sagittae,* discovered to be spectroscopic binaries by Dr. R. H. Curtiss, using the one-prism spectrograph, as announced in *Bulletin* No. 62.

This star is of Type K, with good lines. Though the observed variation is small, there seems to be no doubt of its reality. The period is doubtless several years. The variable velocity was suspected from the third plate by Director Campbell.

Date	Velocity	Observer
1897, November 25.........	+10km	Campbell
	+10.9	Burns[1]
1898, October 11............	+ 9	Campbell
	+6.2	Burns
November 14.........	+ 5	Campbell
	+ 3.8	Burns
1899, August 14............	+ 6	Campbell
	+ 6.0	Burns
August 22............	+ 6	Campbell
	+ 5.5	Burns
September 26.........	+ 7	Campbell
	+ 6.7	Burns
1900, August 12............	+ 7.6	Burns
1901, August 14............	+ 8.0	Burns
September 1..........	+10.2	Burns
1903, September 15.........	+ 7	Curtis
1904, September 7..........	+ 9	Curtis

γ Geminorum ($\alpha = 6^h\ 31^m.9$; $\delta = +16°\ 29'$)

This star's spectrum is of the Sirian type, and the lines are capable of accurate measurement. The variable velocity was discovered by Mr. Burns, from the definitive measures of the third plate.

Date	Velocity	Observer
1899, September 21.........	−17km	Campbell
	−15.4	Burns
October 24...........	−17	Campbell
	−15.1	Burns
1904, January 27............	− 4.7	Burns
February 13*.........	−10.4	Burns

α² Geminorum ($\alpha = 7^h\ 28^m$; $\delta = +32°\ 7'$)

A spectroscopic binary of unusual interest was discovered in *α²* *Geminorum* by Dr. Heber D. Curtis in October 1904. Twenty-five plates secured to date with the Mills spectrograph show a variation in the radial velocity of about 26 km. The observations seem to be

[1] Dr. Joseph H. Moore and Mr. Keiven Burns are Carnegie Institution assistants in spectroscopy. Mr. F. E. Brasch was for a short time the Carnegie Institution computer in this department.

*Added while passing through press.

well satisfied with a period of 9.27 days. Two early plates of this component of *Castor* taken on November 18, 1897, and March 31, 1901, are unfortunately rather poor, so that their value in a more accurate determination of the period is somewhat impaired, and additional plates will be needed before this period can be regarded as definitely established.

As is well known, α^1 *Geminorum*, the fainter component, was found to be a spectroscopic binary by Dr. Bélopolsky at Pulkowa, with a period of 2.934 days.[1]

Both stars are given in the *Draper Catalogue* as of Type A, and in the later Harvard classification as VIII*a*. In the region covered by the remounted Mills spectrograph, λ 4500 central, the spectra of both components are precise duplicates of that of *Sirius*. $H\gamma$ is broad and has not been used in the measures; the magnesium line λ 4481 is very good, and there are numerous other metallic lines, mainly enhanced lines of iron and titanium, with a few apparently due to chromium and barium.

The discovery is of special interest in that *Castor* is thus definitely shown to be a quadruple system. As is well known, *Castor* is one of the most conspicuous of the visual binaries. Its orbit is still somewhat uncertain; the latest and most probable elements are by Doberck,[2] giving a period of 347 years. The preliminary value of the velocity of the center of mass of α^2 *Geminorum* is about +6 km. For α^1 *Geminorum* a corresponding value of −2 km has been derived from a curve depending upon nineteen plates. Applying this relative velocity to Doberck's orbit, we find a parallax of 0".05; but, owing to the uncertainty in the elements of the visual system, this result is of small weight.

Dr. Curtis has in progress a more detailed investigation of the orbits of both systems. With the improved values which will eventually be found for the visual system it should be possible to secure relatively accurate values of the distance, masses, and orbital dimensions of this complicated system.

[1] *Bulletin of the St. Petersburg Academy of Sciences*, December 1896; *Astrophysical Journal*, **5**, 1, 1897.

[2] *Astronomische Nachrichten*, **166**, 145, 1904.

The annexed table gives the results of Dr. Curtis' measurements of the plates secured to date.

Date	Velocity	Remarks
1897, November 18.975.....	+ 1.1km	Poor
1901, March 31.740.....	+17.3	Very poor
1904, September 28.025.....	+ 1.6	
November 9.053.....	+18.9	
9.913.....	+15.9	
22.015.....	+ 4.4	
22.791.....	+ 0.9	
23.056.....	− 1.4	
29.025.....	+11.3	
29.819.....	+ 9.5	
December 6.025.....	+19.0	
7.042.....	+17.4	
8.049.....	+12.7	Not very good
13.986.....	− 3.0	
26.941.....	+13.5	
27.915.....	+ 9.3	
1905, January 1.955.....	+ 9.5	
2.652.....	+18.2	Very weak
2.994.....	+17.2	
3.951.....	+16.1	
4.938.....	+11.2	
9.875.....	− 8.5	
10.072.....	− 9.0	
10.997.....	+ 5.8	
11.049.....	+ 6.4	

η Boötis ($\alpha = 13^h\ 49^m.9$; $\delta = +18°\ 54'$)

This star is type G, with very good lines.

Date	Velocity	Observer
1897, February 3..........	− 0.6km	Campbell
April 20............	− 2	Reese
21............	− 4	Reese
May 12............	− 2	Campbell
1899. February 7..........	− 2.2	Stebbins
1901, May 19............	− 4	Reese
	− 4.9	Stebbins
1903, May 24............	+ 7	Curtis
	+ 6.9	Burns
1904, March 2............	− 8.2	Moore
March 31..........	− 4.9	Moore
May 2............	− 6	Curtis
	− 7.6	Moore
June 14............	−10	Curtis
26............	− 6	Curtis
	− 7.3	Moore
1905, January 4..........	+ 5.5	Moore

The period is probably several years. The variable velocity was discovered by Dr. Moore.

ξ Serpentis ($\alpha = 17^h\ 32^m$; $\delta = -15^\circ\ 20'$)

This star is given in the *Draper Catalogue* as Type A. Its spectrum contains many metallic lines, and in general resembles that of *Sirius*.

Date	Velocity	Observer
1902, July 1	-45.0^{km}	Burns
1903, June 22	-62	Curtis
	-60.3	Moore
1904, May 30	-39	Curtis, Underexposed
	-39.2	Moore
June 13	-49	Curtis
	-49.3	Moore
June 14	-41	Curtis
	-42.7	Moore

The period is probably short. The variation was discovered by Dr. H. D. Curtis from the third plate.

ζ Lyrae, pr. ($\alpha = 18^h\ 41^m.3$; $\delta = +37^\circ\ 30'$)

This star is of Type A; it has numerous titanium lines and enhanced iron lines.

Date	Velocity	Observer
1902, July 15	$+21^{km}$	Curtis
1903, July 21	-31	Curtis
1904, May 15	-5	Curtis
August 1	$+22$	Moore

The variation was discovered by Dr. H. D. Curtis from the second plate.

τ Sagittarii ($\alpha = 19^h\ 0^m.7$; $\delta = -27^\circ\ 49'$)

This star is of Type K, with very good lines. Its variability was suspected by Dr. Curtis in May 1903, and confirmed in October 1903. It has already been announced by Wright in *Lick Observatory Bulletin* No. 60 as one of the results of the D. O. Mills Expedition to the Southern Hemisphere.

Date	Velocity	Observer
1902, August 17	$+34^{km}$	Stebbins
1903, May 6	+50	Curtis. Poor plate
October 25	+24	Curtis
1904, May 12	+51	Palmer
June 7	+60	Palmer

The last two plates were taken at the Southern Station.

71 Aquilae ($\alpha = 20^h\ 33^m$; $\delta = -1°\ 27'$)

This star is of type H, with very fair lines.

Date	Velocity	Observer
1900, June 18	-2^{km}	Wright
July 10	−5	Wright
1903, September 22	+2	Curtis
	+3.0	Brasch
1904, August 30	−11	Curtis
	−11.3	Brasch
August 7	−12	Curtis
	−12.7	Brasch

The variable velocity was discovered by Dr. H. D. Curtis from the third plate.

LICK OBSERVATORY,
UNIVERSITY OF CALIFORNIA
January 25, 1905.

ON THE RADIAL VELOCITIES OF *POLARIS*, η *PISCIUM*, ϵ *AURIGAE*, AND β *ORIONIS*

By W. W. CAMPBELL and HEBER D. CURTIS

a Ursae Minoris ($\alpha = 1^h\ 22^m.0$; $\delta = +88°\ 46'$)

Groups of plates of *Polaris* taken at intervals during the past four years show that the velocity of the center of mass of the rapid pair of this triple system is changing in a very regular manner along a velocity-curve which indicates a period of at least eleven or twelve years. The period may be considerably longer than this, but the observations do not as yet permit even an approximate determination of its length. The accompanying table gives the positions of the *minima* of the velocity-curve of short period (3 days, 23 hours, 14 minutes) at the dates indicated. These values have been determined graphically; and it is to be expected that a definitive discussion of the data will change them slightly.

Date	Positions of Minima
1896.9	−20.67 km
1899.8	−14.22
1900.6	−14.64
1901.4	−16.32
1902.6	−16.79
1903.0	−17.18
1903.7	−17.84
1904.5	−18.52

The position of the series of 1901.4 falls nearly a kilometer off the curve; the agreement of the others is very close.

η *Piscium* ($\alpha = 1^h\ 26^m.2$; $\delta = +14°\ 50'$)

In the *Astrophysical Journal* for May 1904 Professor Lord has published eleven radial velocities of η *Piscium*. They range from +9.5 to +25.4 km, and he suspects that the velocity varies in a long period.

The following observations have been secured at Mount Hamilton:

Date	Velocity	Observer	Remarks
1897, September 14	+16.6	Burns	
1898, August 19	+16.5	Burns	
August 29	+15.8	Burns	
October 3	+13.3	Burns	Plate overexposed
1904, July 6	+15.6	Curtis	
July 18	+16.1	Curtis	
October 17	+15.5	Curtis	

Professor Lord's plates were all secured between the dates December 15, 1901, and January 9, 1904, during which interval no observations were made here. Our results neither prove nor disprove that the star is a spectroscopic binary. Further observations are desirable before a decision can be made.

ϵ *Aurigae* ($\alpha = 4^{h}\ 54^{m}.8$; $\delta = +43^{\circ}\ 41'$)

This star has been announced as a spectroscopic binary by Professor Vogel.[1] The first few plates of this star taken with the Mills spectrograph showed considerable variation, and it was placed on the "suspected list" early in 1900. Recent definitive measures of these plates fully confirm its binary character.

Date	Velocity	Observer	Remarks
1897, January 7	+ 9	Campbell	Very poor plate
1899, December 18	+ 4.2	Burns	
1899, December 27	+ 5.7	Burns	
1900, January 17	+10.0	Burns	
September 24	− 2.6	Burns	
1903, December 29	− 5	Moore	
	− 3	Brasch	

The period as pointed out by Professor Vogel is doubtless several years.

β *Orionis* ($\alpha = 5^{h}\ 9^{m}.7$; $\delta = -8^{\circ}\ 19'$)

From fourteen Potsdam spectrograms of this star, made in the years 1888–1891, velocities ranging from +3 to +34 km per second were obtained, and Professor Vogel strongly inclined to the view that the velocity is variable.[2] Nineteen spectrograms by Frost and Adams at the Yerkes Observatory, between September 1901 and

[1] *Astrophysical Journal*, **17**, 243, 1893.

[2] *Potsdam Publications*, **7** (I), 146–151, 1892.

March 1902, give results ranging from +14.9 to +23.4 km, the mean value being +20.7 km, but these observers attribute the observed variations entirely to the difficulty of measuring the wide lines in this spectrum.[1]

The following observations have been secured at Mount Hamilton with the Mills spectrograph. Where two measures of a plate are given, the first is approximate and the second definitive.

Date	Velocity	Observer	Remarks
1897, October 6	+16 km	Campbell	
	+16	Burns	
December 15	+20	Campbell	Poor plate
	+25	Burns	
1900, February 5	+18	Campbell	
	+15	Burns	
1901, October 15	+20	Burns	
1904, January 26	+18	Moore	

The mean value of the definitive measures is +18.9 km. These photographs were taken without preliminary tests to determine what exposure time would define the lines most clearly; and, as a result, the negatives are for the most part overexposed, but none have been rejected. Considering the small number of lines available, and their poor quality, we may say that these results give no evidence of variable velocity. Properly timed exposures would, in our opinion, reduce the observed range appreciably.

LICK OBSERVATORY,
UNIVERSITY OF CALIFORNIA,
January 25, 1905.

[1] *Publications of the Yerkes Observatory*, **2**, 52–61, 1903.

Minor Contributions and Notes.

ON THE COMPARATIVE LUMINOSITY AND TOTAL RADIATION OF THE SOLAR CORONA

In my report of the bolometric measurements made at the eclipse of May 28, 1900,[1] I stated that the luminosity of the inner corona, as compared with its heating effect, is so great that it is difficult to attribute the coronal radiation to the incandescence of particles of matter made hot by their proximity to the Sun, or even to suppose that the corona shines chiefly by reflected photospheric rays.

Professor Arrhenius has recently controverted[2] the former inference on the ground that the supposed incandescent particles observed by the bolometer can be computed to maintain a temperature of about 4620° absolute, and that the spectrum of a black body at this temperature is sufficiently luminous in comparison with its total radiation to yield the results observed. Partly on account of an ambiguity of my statement of the position of the bolometer, Professor Arrhenius has computed the temperature only of the *hottest particle* which took part in the radiation observed, apparently without considering (*a*) that the farther edge of the bolometer strip was 1.2 mm instead of 0.2 mm from the image of the solar disk, and the ends of the strip more distant still; or (*b*) that all the particles along the line of sight from the nearest to the remotest limits of the corona took part in the radiation, as well as those situated immediately opposite the center of the Sun, so that the effective mean temperature of the supposed hot particles is lower than the temperature he has computed.

It follows from a recomputation that the mean effective temperature of the observed part of the corona is about 3000°, assuming that it is composed of "black body" particles. If, further, we assign the proper luminous effectiveness to the different spectral rays, allow for the absorption of our atmosphere, and assume that the coronal region in question is only of the same average brightness as the Moon, it would seem that, if its radiation is mainly due to the incandescence of particles heated to this temperature by proximity to the Sun, its heat should have been many times as great as

[1] *The 1900 Solar Eclipse Expedition of the Astrophysical Observatory of the Smithsonian Institution*, p. 26.

[2] *Lick Observatory Bulletin* No. 58; *Astrophysical Journal*, **20**, 224, October 1904.

was actually observed by the bolometer. An independent computation, based on the comparative light and heat of the Sun and Moon, yields confirmative results.

It still seems to me, then, that the results of the bolometric experiments are incompatible with the hypothesis of a corona radiating chiefly by incandescence.

S. P. LANGLEY.

SMITHSONIAN INSTITUTION,
Washington, D. C.,
January 1905.

NOTE ON NARROW TRIPLETS IN THE SPECTRA OF CALCIUM AND STRONTIUM

In the course of a somewhat extended investigation of the spectra of the elements of the second column of Mendelejeff's table, the writer has made a series of grating photographs, extending from λ 8000 to λ 2200. The apparatus and method were the same as those used in the study of the lithium family.[1] A preliminary survey of these films was made some time ago, and the series in the spectrum of strontium, which was recently announced by Fowler,[2] was noticed, along with some other new lines. A precisely similar series was also noticed in the spectrum of calcium; its terms are shown in the accompanying table.

NARROW TRIPLET SERIES IN CALCIUM SPECTRUM

Wave-Length	Frequency Intervals
4586.12 4581.66 4578.82	21.20 13.53
4098.82 4095.25 4092.93	21.30 13.80
3876.2 3872.9 3870.9	22.00 13.34
3754.2 3750.9 3749.0	23.4 13.5
3678.5 3675.5 3674.4	22.2 8.2

[1] *Astrophysical Journal*, **20**, 188, 1904. [2] *Ibid.*, **21**, 81, 1905.

The first two of these triplets were measured by Kayser and Runge; the last three have not, so far as the writer knows, been noticed before. The intensities of the lines decrease, as they should, from triplet to triplet, with decrease in wave-length. The measurements here given may not be very accurate, as the lines are both faint and diffuse; the values for the last triplet, especially, are likely to be considerably in error. These lines are best shown by a photograph taken of the arc between *copper* poles, moistened with calcium-chloride solution. Such an arrangement prevents the appearance of the carbon bands, which would otherwise obscure all faint lines in this region.

The first lines of these triplets satisfy the formula

$$1/\lambda = 28930.0 - \frac{109675}{(n+0.8902)^2+0.2461},$$

where n has the values 3, 4, 5, 6, and 7, and 109675 is a universal series constant. This formula calls for another term near λ 6180, but, though there are lines in that neighborhood, none can be found with the required separations.

Another triplet, given by Kayser and Runge, beginning at λ 5601.51, has a similar separation, but its lines are irregular both in position and relative intensities, and cannot be classified with the others, if the series is to be represented by any of the usual formulæ. There are still other triplets of nearly the same separations, beginning at $\lambda\lambda$ 5270.45, 4512.73, 4059.1, and 3844.0, of which the last two are probably new. This set looks, at first sight, as though it might form a companion series, but such is apparently not the case, though it comprises all the remaining narrow triplets of this spectrum that have so far been found. The strontium spectrum shows indications of a similar set of lines, but this is irregular in the same way as the calcium group, and still less complete.

The writer's measurements of the lines in Fowler's series in the strontium spectrum agree closely with those given by him, as do also those of King[1] for the triplet near λ 4087. A new term should be added to the series at λ 3867.3 $\pm$ 0.2 (only the first line can be seen on the writer's photographs); the position for this line, calculated from the second formula given by Fowler, is λ 3867.46.

F. A. SAUNDERS.

SYRACUSE UNIVERSITY,
January 1905.

[1] *Ibid.*, **18**, 129, 1903.

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THE OPTICS OF THE SPECTROSCOPE

By ARTHUR SCHUSTER

1. Lord Rayleigh's investigations on the resolving power of prisms and gratings have enabled us to calculate the theoretical efficiency of any spectroscope. When those researches were published, I was at work investigating spectra of feeble intensities which rendered it necessary to open the slits considerably beyond the point at which Lord Rayleigh's equations became applicable. It was not quite clear that with a wide slit the resolving power, as distinguished from dispersion, remained the sole determining factor in the calculation of the efficiency of spectroscopes, but I proved this to be the case.[1] It seemed convenient to introduce a new quantity, which I called the "purity" of a spectrum, and which was intended to serve as an indicator for the efficiency of the instrument with wide slits, just as the resolving power was the indicator for narrow slits. Making a certain assumption as regards the condition of resolution and writing

$$P=\frac{\lambda}{\lambda+d\psi}R, \tag{1}$$

where P is the purity, R the resolving power, ψ the angle subtended by the diameter of the collimator lens at the slit, d the width of the slit, and λ the wave-length, I showed that two wave-lengths differing by $\delta\lambda$ were resolved when $\delta\lambda=\lambda/P$.

[1] Art. "Spectroscopy," *Encyclopædia Brittanica.*

Shortly afterward Professor Wadsworth subjected equation (1) to a criticism which in the main was justified, and he entered into an elaborate discussion of the whole problem. In the course of his analysis he arrived at the paradoxical result that there is a certain width of slit for which its power to resolve close doublets is greatest, so that if the slit be narrowed beyond that width, resolving power is diminished.

Elementary considerations show that this result cannot be correct, but, as it has never been publicly challenged, and has been reproduced in Kayser's *Handbuch*, it may be useful to disprove it formally. In Fig. 1 let the curved line represent the distribution of intensity in

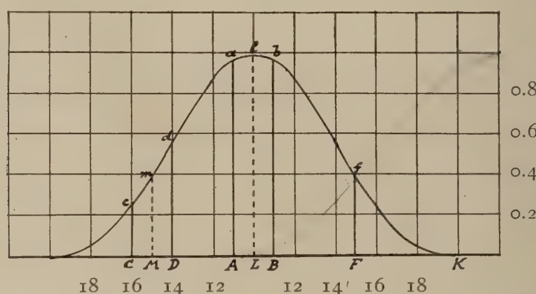

FIG. 1.

the diffraction image of an indefinitely narrow slit, and let Aa and Bb be the positions of geometrical images of the two edges of the slit, the diffraction image being considered to lie in the focal plane of the telescope, which also contains the geometrical image of the slit. If the slit be widened or narrowed symmetrically, the intensity in the central line of the diffraction image is easily shown to be proportional to the area $ABba$. On the same scale, the area $CDdc$ would represent the intensity of the image along its central line Mm.

Lord Rayleigh has found that with a narrow slit two close lines are fairly resolved by means of eye observations when they are at such a distance from each other that the center of one diffraction image falls on the first zero of intensity of the other. If in Fig. 1 the center of a second diffraction image is at K, the distribution of light in the combined images has a minimum along a line Ff, where F is half-way between L and K. The intensity along this line is 0.81 of

the maximum intensity, and Professor Wadsworth takes this fraction to be in all cases that required for the intensity at the minimum, if the lines are to be resolved. Accepting this criterion, consider the effect of widening the slit on the distribution of intensity in the diffraction image of a single line. If at any point of the intensity-curve the outline *cmd* were a straight line, the intensity at that point would vary in exact proportion to the width of the slit. Neglecting, therefore, the curvature at all points, the distribution of intensity would not be altered by a change in the width of the slit. But when the curvature is taken into account, the increase in intensity is more or less rapid than the increase in the width of the slit, according as the curve is convex or concave when looked at from the axis of abscissæ. Near the central line the concavity is greatest, and diminishes toward the two sides; hence it follows that the central intensity increases less with a widening of the slit than the intensity at any other part of the diffraction image. If two lines are at such a distance that with a very narrow slit they are just resolvable, the ratio of the minimum to the maximum is $2Ff/Ll$. As widening the slit has just been shown to increase the intensity at Ll less than that at Ff, this ratio must be increased; and if the lines were just on the point of resolution with a narrow slit, they cease to be resolved when the slit is widened.

In order to show where the error in Professor Wadsworth's treatment occurs, I have plotted in Fig. 2 the curve AC_1B which is represented by his formula, the ordinates standing for the distances of the two components of a doublet which is just on the point of resolution, and the abscissæ denoting the widths of the slit. The unit of length in both cases is half the width of the central diffraction band. The drop in the curve between A and C_1 shows the improvement in resolution which is indicated by Professor Wadsworth's formula. But the curve ACB, which has been drawn by means of accurate calculation, gives a steady diminution of resolving power with increased width of slit. This is as it should be. Professor Wadsworth obtained his formula by interpolation between four points. Of these A is one, the second is at the point marked P in the figure, and the two others were at the positions calculated for slits twice and three times as great as that to which P refers. The minimum given by his formula has been obtained simply in consequence of an arbitrary manner of

interpolation. No one joining the points B_1 and A would, of course, do so by means of a curve having, without any apparent reason, a dip at C_1. Professor Wadsworth was misled by not plotting the distance of resolution, but this distance diminished by the slit-width. This explains his paradoxical result.

2. Although Professor Wadsworth has brought out many interesting points in the course of his investigations, he has, in my opinion,

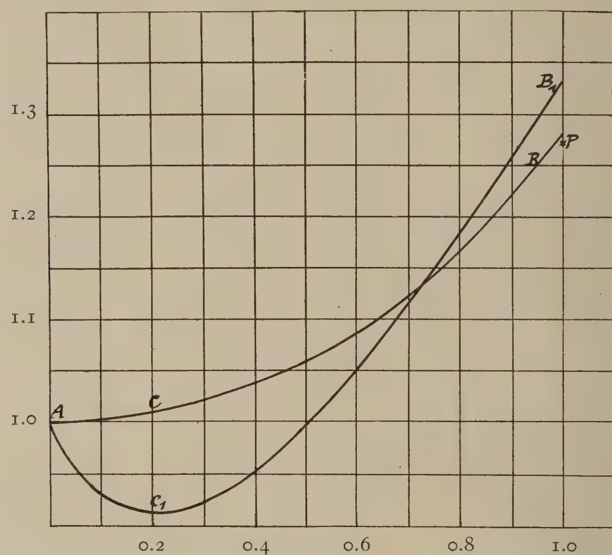

FIG. 2

done harm by depriving the subject of its original clearness and simplicity. It seems therefore necessary to start afresh by asking ourselves what objects a theoretical discussion on resolving powers may usefully serve. There can be no doubt as to the fundamental value of Lord Rayleigh's original equations. They allow us to compare the efficiency of gratings and prisms, or again of large and small prisms. When we have solved in our minds what kind of resolving power is wanted, we may without difficulty construct an instrument which shall fulfil the requirements. Great refinement of accuracy is not necessary for the purpose, nor is it possible, because other circumstances come into action, notably luminosity. My own investigations of very weak spectra led me, as already men-

tioned, to introduce the question of slit-width. Although I think I was justified to do this, I have often regretted it, because I set the ball rolling, and it went on rolling, but unfortunately in the wrong direction. Professor Wadsworth, for instance, extended my equation by including the case that each component of the doublet which is to be resolved is not quite homogeneous and includes a finite range of wave-lengths. This meant throwing the whole question into confusion. When we discuss the power of an instrument, we must clearly separate those conditions which concern the instrument from those which do not. No one would think of asserting that the power of a telescope is less when it tries to distinguish details in a nebula than when it examines close double stars, for the telescope is not responsible for the absence of sharp detail in a nebula. Its object is to give images as nearly corresponding to reality as possible, and the extent to which that object is realized depends purely on instrumental conditions. Similarly, the main object of a spectroscope is to form a pure spectrum, and the extent to which that object is realized depends on the prisms or gratings and on the width of the slit, and on nothing else. The separation of double lines is a convenient test of resolving power, but the main purpose of the spectroscope is the correct representation of the distribution of energy in a spectrum, whether continuous or discontinuous. I do not deny the utility of investigating under what conditions bands of finite width are resolved, but the discussion should be kept clear of all connection with formulæ representing resolving powers.

Owing to the finiteness of the waves of light, each wave-length, even in a so-called pure spectrum, encroaches to some extent on a neighboring one. We require some kind of simple measure as to the extent of this trespass. In my first treatment of the subject I endeavored to obtain this by neglecting everything in the diffraction image beyond the first band. If that were allowable, each wave-length would spread over a certain finite range and not beyond. If 2ϵ be the width of the first band in the diffraction image of a narrow line, and σ the width of the slit-image, each wave-length would spread through a distance $\frac{1}{2}\sigma+\epsilon$ to either side of its center. Two lines would be completely separated when their distance is $\sigma+2\epsilon$. But Lord Rayleigh showed that in the case of nearly homogeneous lines the

resolution is already noticeable when their distance is ϵ. I therefore made the assumption, which seemed to me to be the most simple one to make, that with wide slits resolution begins when the distance between the lines is $\sigma+\epsilon$. Equation (1) is deduced under this condition. Professor Wadsworth showed conclusively, however, that, owing to the rapid falling off of the light near the edge of the image of an extended luminous surface, the distance between lines may be appreciably reduced beyond the point at which, according to my formula, resolution should begin. This rapid diminution in intensity may be understood at once, if it be remembered that at the edge of the geometrical image of a surface the intensity is already reduced to one-half, so that it requires very little separation between the geometrical images of two surfaces to produce a sensible diminution of light between them. Though equation (1) may therefore serve to give a rough and ready expression of purity, it gives incorrect results when the resolution of narrow doublets is in question. Professor Wadsworth's test of resolution, that the intensity at the point half-way between the centers of the overlapping lines shall be a definite fraction of the intensity at the center of each of the images, has the disadvantage that it is based on visual observation, and is not necessarily applicable directly to photographic or bolometric measurements. If I have left the criticism of Professor Wadsworth's results stand over for so long a time after their appearance, it was chiefly because I was not quite satisfied with any way of reconciling the different considerations of which account has to be taken. After much hesitation, I wish now, however, to submit the following proposals, which seem to me to meet the case in a fairly simple manner, and have the advantage of keeping Professor Wadsworth's criterion in practice while putting its definition on a somewhat wider basis.

In the image of a very narrow slit the intensity at a distance ϵ from the center is zero; the intensity at a distance $\frac{1}{2}\epsilon$ is 0.40528 that of the center. We may therefore say that the line spreads out on either side to a point which is at a distance twice that of the point at which the intensity is equal to the above fraction. Let us generalize that definition and say: The sensible image of a slit of finite width spreads through a distance δ to either side of its center, such that the intensity at a distance $\frac{1}{2}\delta$ is 0.40528 that of the intensity at the center.

Two lines at a distance 2δ from each other may then be said to be completely resolved, inasmuch as their wave-lengths do not trespass sensibly on each other.

Observation shows however, that visual resolution already begins when their distance is δ. We shall adopt this distance as the criterion of visual resolution.

If a point of the spectrum defined by λ is encroached upon according to the above definition by waves on either side as far as $\lambda + \delta\lambda$ and $\lambda - \delta\lambda$, we write

$$P = \lambda/\delta\lambda,$$

and call P the purity of the spectrum. Two lines will be *completely* separated when they are at a distance $\delta\lambda$, which is equal to $2\lambda/P$, and visual resolution begins when their difference of wave-length is λ/P.

For very narrow slits the equations are the same, but the resolving power R replaces the purity P. Purity is proportional to resolving power, but also depends on the width of the slit. If we write

$$P = pR \tag{2}$$

p may be called the purity factor. Its values for different widths of slit are given in Table III.

The only thing that is arbitrary in the above definitions is the fixing of a definite limit to which wave-lengths spread on either side, as this implies the neglect of all light which lies beyond these limits. But some arbitrary convention is necessary, and we are justified in giving up purposely refinement of accuracy in order to obtain a ready guidance in our choice of instrument and of width of slit. From this point of view, I cannot find any simpler definitions than the ones chosen.

I do not think it will be necessary to introduce other factors for photographic or bolometric investigations. In the case of the bolometer much depends on the manner in which that instrument is applied. It is beside the mark to say that the bolometer can detect smaller differences of intensity than the eye, because it is a question, not only of observation, but also of interpreting the observations. Supposing there is a falling off in intensity at any point in the spectrum, we do not know whether to interpret this as due to a partially overlapping doublet, or to a narrow band having a minimum of light

at the place where the falling off is observed. After all, the test of resolution usually applied presupposes that we know beforehand that we are dealing with a doublet. If that is not the case, we must increase the power until the resolution is complete. This consideration only shows once more that refinement is impossible. If the performances of different instruments, or of the same instrument with different widths of slit, are to be compared, the reduction of intensity chosen as a test of resolution may be altered within wide limits without detracting from the values of the indications it gives. We fix the fraction once for all for the sake of convenience, and may adopt the same number whether the registration is visual, photographic, or radiometric. We may then discuss whether in particular cases resolution is obtained more or less readily in practice than according to formula (2).

3. The suggested definition, as already pointed out, implies the neglect of a certain amount of light. For narrow slits the light neglected is approximately that which lies beyond the central diffraction band. It may therefore be of interest to determine how much of the total light is actually concentrated in that band. Table I gives the numbers representing the intensity of successive bands. The second column gives the energies of light in half the first band and in each

TABLE I

Order of Band	Relative Intensities		Sum of Intensities Total Light $= 1$
	Total Light $= \pi$	Total Light $= 1$	
Half first band	1.41843	0.45150	0.90300
Band 2	.07401	.02356	.95012
Band 3	.02587	.00824	.96660
Band 4	.01310	.00417	.97494
Band 5	.00790	.00251	.97996
Band 6	.00528	.00168	.98332
Band 7	.00378	.00120	.98572
Band 8	.00283	.00089	.98750
Band 9	.00220	.00070	.98890
Band 10	.00176	.00056	.99002
Band 11	.00144	.00046	.99094
Sum	1.55660	.49547	....

NOTE.—The number given in the first row of the last column represents the energy of the light in the whole of the first band, and the other numbers in the same column include the energies of both bands of the same order.

successive band, while the third column gives the total energy of the central and lateral bands up to and including the two which are of the order marked in the first column. It is seen that 90 per cent. of the light goes to form the central band, that 2 per cent. goes to form the bands of higher order than the fifth, and that 1 per cent. of the total light goes to form the bands of higher order than the eleventh.

Although a considerable amount of light is therefore neglected in our convention as regards the extent of trespass, yet no practical disadvantages result therefrom, especially as the light neglected is spread over a considerable range of wave-lengths, so that within any small range of periods the total energy is exceedingly small.

4. If σ is the width of the geometrical image of the slit measured in a certain unit, and x the distance in the same unit from the central line of the image, the intensity in the diffraction image of the slit at the distance from the center x is

$$\int_{x-\frac{\sigma}{2}}^{x+\frac{\sigma}{2}} \alpha^{-2} \sin^2 \alpha \, d\alpha \tag{3}$$

The unit distance here is such that the first minimum with an indefinitely narrow slit occurs when $x = \pi$.

I have calculated a table of the integral

$$\int_{0}^{x} \alpha^{-2} \sin^2 \alpha \, d\alpha \quad ,$$

where x was gradually increased by steps of 0.1π from 0 to 5π. By means of this table, which it is not necessary to reproduce here, the integral (3) could be calculated for different values of σ and x. Table II giving the distribution of light for different slit-widths was thus obtained. The scale of distance in this table has been changed so that the distance previously represented by π is now unity. To reduce to centimeters we should have to multiply all quantities by $f_1\lambda/D_1$, where f_1 and D_1 are the focal length and diameter of the telescope. The slit-widths as given in the headings of the columns are given in terms of the slit-factors to be defined presently. They may be reduced to centimeters by multiplication with $f\lambda/D$, where

TABLE II

DISTRIBUTION OF INTENSITY IN IMAGES OF SLITS OF FINITE WIDTH

The unit of distance is the half-width of the central diffraction band in the focal plane of the telescope. The width of slit corresponding to the headings of the different columns is obtained by multiplying the numbers given, with the product of the wavelength and focal length of collimator and dividing by the diameter of the collimator lens.

Distance from Center	$\sigma=0$	$\sigma=0.8$	$\sigma=1.6$	$\sigma=2.4$	$\sigma=3.2$	$\sigma=4.0$	$\sigma=8.0$	$\sigma=12.0$
0	1	1	1	1	1	1	1	1
0.1	0.9675	0.9680	0.9695	0.9719	0.9752	0.9792	0.9999	0.9994
.2	.8751	.8770	.8825	.8916	.9040	.9192	.9983	.9978
.3	.7368	.7406	.7518	.7702	.7954	.8265	.9917	.9962
.4	.5728	.5785	.5956	.6239	.6627	.7108	.9753	.9952
.5	.4053	.4126	.4345	.4708	.5209	.5834	.9441	.9949
.6	.2546	.2627	.2872	.3279	.3845	.4560	.8946	.9946
.7	.1353	.1434	.1676	.2082	.2652	.3384	.8252	.9918
.8	.0547	.0617	.0830	.1190	.1705	.2379	.7374	.9831
.9	.0119	.0173	.0336	.0618	.1030	.1588	.6356	.9640
1.0	0	.0034	.0138	.0325	.0610	.1017	.5261	.9306
1.1	.0080	.0095	.0143	.0237	.0395	.0646	.4166	.8797
1.2	.0243	.0243	.0247	.0266	.0320	.0436	.3146	.8105
1.3	.0392	.0384	.0362	.0334	.0319	.0339	.2261	.7243
1.4	.0468	.0457	.0427	.0383	.0338	.0308	.1550	.6252
1.5	.0450	.0442	.0420	.0385	.0343	.0304	.1027	.5190
1.6	.0358	.0356	.0349	.0337	.0321	.0302	.0681	.4128
1.7	.0230	.0233	.0244	.0259	.0274	.0287	.0481	.3136
1.8	.0108	.0116	.0139	.0174	.0216	.0258	.0387	.2272
1.9	.0027	.0036	.0064	.0108	.0162	.0221	.0356	.1575
2.0	.0000	.0008	.0033	.0072	.0123	.0181	.0352	.1059

f and D are the focal length and diameter of the collimator lens. Having therefore measured a slit-width, d, we calculate $dD/f\lambda$. The distribution of light is then found in the vertical column headed by the number thus calculated. The intensities are all given in terms of the intensity at the center of the image.

Having found the distribution of light, we determine the factor of [illegible] by finding in the first instance the distance at which the [illegible] is equal to 0.40528. This I did by a process of interpolation, using finite differences. Doubling the distance thus calculated, we obtain the distance of resolution. The results are collected in Table III. The unit distance is again half the width of the central diffraction image when the slit is indefinitely narrow. Column I gives the width of the slit in this unit.

It is of advantage to refer all slit-widths to some one width conveniently chosen and called the "normal width." In investigating

TABLE III

CONNECTION BETWEEN PURITY AND WIDTH OF SLIT

I Width of Slit	II Slit Factor	III Distance of Resolution	IV Purity Factor	Relative Intensities	
				V Intensity 1 for Normal Width	VI Intensity 1 for Infinite Width
0	0	1.0	1.0	0	0
0.1	0.4	1.002	0.998	0.406	0.100
.2	.8	1.009	.991	.805	.198
.25	1	1.014	.986	1.000	.246
.3	1.2	1.021	.980	1.191	.293
.4	1.6	1.038	.964	1.558	.383
.5	2.0	1.060	.943	1.902	.467
.6	2.4	1.089	.918	2.217	.545
.7	2.8	1.124	.889	2.500	.615
.8	3.2	1.168	.856	2.751	.676
.9	3.6	1.221	.819	2.967	.729
1.0	4.0	1.283	.780	3.148	.774
1.2	4.8	1.438	.695	3.415	.839
1.4	5.6	1.624	.616	3.571	.878
1.6	6.4	1.823	.549	3.646	.896
1.8	7.2	2.022	.495	3.670	.902
2.0	8.0	2.221	.450	3.674	.903
3.0	12.0	3.214	.311	3.789	.931
D very large		D+0.096		4.0689	1.000

The width of slit in centimeters is obtained by multiplying the first column with λ/ψ, where ψ is the angle subtended by the diameter of the collimator lens at the slit.

the question of deterioration of images owing to aberrations or other defects, Lord Rayleigh has generally admitted one-quarter of a wave-length as the limit of the allowable deviation from the ideal wave-front, if the image is not to suffer appreciably. Looked at from this point of view, an extreme difference of path of one-quarter wave-length from one of the edges of the slit to the nearest and farthest points of the collimator lens should give images as good as if the slit were an indefinitely narrow line. Consequently, we may fix on this width as being that of the normal slit. I call "slit factor" the width of a slit expressed in terms of the normal slit. These factors are entered in Column II of the table. Column III gives the distance of resolution, which, for an infinitely narrow slit is unity; column IV gives the purity factors, which are equal to the reciprocals of these distances of resolution. This column therefore expresses what fraction of the highest possible resolving power is retained under

different conditions of slit-width. In Column V of Table III I have given the central intensities of the images in terms of the intensity for the normal width of slit, while Column VI gives the same intensities in terms of the possible maximum intensity, which is that obtained with an infinitely wide slit. A comparison of Columns IV and V will help in each case to determine our choice as regards width of slit. The normal slit, for which the slit factor is unity, will be seen to give us a resolving power about 1.5 per cent. less than the maximum power. If we do not mind a loss of purity of 6 per cent. we may set the slit at 2, and obtain nearly double the amount of light. We may treble the light, retaining about 80 per cent. of purity, but a total intensity of 3.67 times that obtained with a normal slit is accompanied by a loss of half the resolving power. When this point has been reached, a further widening of the slit leads to a great deterioration of purity without material increase of light. It will, however, appear presently that the loss of light due to diffraction renders a further slight increase of resolving power advisable.

We are led to the general conclusion that spectroscopes intended for observations in which light is a consideration should be constructed so as to give about twice the resolving power of that actually aimed at. We may then set the slit so that its factor is 7.2.

It is somewhat remarkable that the one statement in my previous treatment of purity and resolving power which, though frequently quoted, has never been challenged, is the only one which is really wrong. I stated that the intensity at the center of the diffraction image increases with the widening of the slit until the slit-image had a width equal to one-half the width of the diffraction image. This was an error. I was then writing under the supposition that all the light beyond that contained in the central band may be neglected, and if that is the case, the light increases until the slit-image has a width equal to that of the width of the diffraction image, or double the width given in my statement. The slit-factor in that case would be 8. Taking account of the light which forms the lateral bands, the increase in intensity must of course go on indefinitely with an increase in the width of the slit. Table III shows, however, that this increase is very slow if the slit-factor is greater than about 7.

The following statement in my *Encyclopædia* article has also been

criticised: "As a matter of fact, spectroscopists generally work with slits wider than that which theoretically gives full illumination. The explanation of the fact is physiological, visibility depending on the apparent width of the object."

The width of slit necessary for full illumination was, as pointed out above, underestimated, and this no doubt partly accounts for the discrepancy alluded to in the passage quoted. But the physiological effect was not invented, as my critics seem to have believed, to serve as an explanation *ad hoc*, but it is a *vera causa*, and should be familiar to spectroscopists accustomed to eye-observations. Let those who doubt hunt for the violet potassium line in a Bunsen burner, and, when found, measure the width of the slit they have used.

5. The above investigation is based on the supposition that the slit behaves like a self-luminous source, each part of which acts independently of the other. In laboratory experiments this may be secured by forming an image of the source of light on the slit. When the slit is narrow, the condensing lens must subtend a larger angle at the slit than the collimator lens, to prevent loss of light by diffraction. This loss may be very considerable, and if the slit has its normal width, the angular aperture of the condensing lens, as seen from the slit, should, if possible, be four times as great as the angular aperture of the collimator lens.

In the case of astronomical work, the angular aperture of the condensing lens is given, and to save loss by diffraction, the angular aperture of the collimator lens would have to be reduced so as to allow a wider opening of the slit. The gain would, however, be more than balanced by the loss of light due to the cutting out of the undiffracted rays coming from the outside portions of the telescope lens.

It is not quite easy to calculate the loss of light due to diffraction when a condensing lens is used. Fortunately Mr. J. H. Moore has recently published[1] experimental data which show that it is not much different from that found when a parallel beam falls on the slit. The effect of diffraction would in that case be to reduce considerably the intensity factor given in Column V of Table III for slits having

[1] *Astrophysical Journal*, **20**, 285, 1904.

a slit factor less than 8, but it would not much effect the light if the slit had that width. There is no way of avoiding this, as the width of slit is fixed by the angular aperture of the collimating lens, and that again is fixed by the angular aperture of the telescope lens. The remedy proposed by Mr. Moore of increasing the length of the collimator would not be effective unless it were accompanied by an increase of resolving power. We must face the loss of purity, and design our spectroscopes to have about two and one-fourth times the required resolving power. A slit factor equal to 8 will then give us practically as much light as can be secured.

With respect to star work, it should, however, be remembered that if definition were perfect, the slit might be dispensed with altogether. The slit in that case could only impair, but never improve, the sharpness of the spectroscopic lines. If a slit is found of advantage, it is only on account of the unrest of star images due to atmospheric causes. If the tremors of the star images are sufficiently rapid, we may consider the case covered by the previous discussion; and the observed results seem to be in agreement with this view.

THE UNIVERSITY,
Manchester, England,
December 1904.

SOME NEW DETERMINATIONS OF THE REFLECTING POWERS OF GLASS AND SILVERED GLASS MIRRORS[1]

By C. A. CHANT

I. REFLECTION FROM METALS

The question of reflecting power is of great importance from both the theoretical and the practical point of view; and it is not surprising, therefore, that numerous investigations have been made upon it. Lord Kelvin has proposed the word "reflectivity" to designate the ratio of the whole reflected to the whole incident light, and it will be used with that meaning in the present paper.

The first precise measurements were probably made by W. Herschel.[2]

He used a photometric method suggested by Bouguer,[3] and measured the reflectivity of one of his specula for nearly perpendicular incidence. He found that it returned 67.262 per cent. of the incident light.

About thirty years later Potter[4] made similar experiments. Potter made his own mirrors, and, becoming expert at polishing, he wished to compare his work with Herschel's. He noted, also, that Newton[5] had assumed that more light was reflected as the angle of incidence was increased, and he determined to test this statement.

Potter also used a modification of Bouguer's photometer, and he was astonished to find his experimental results at variance with Newton's "obvious observation." For a plane mirror of speculum metal the reflectivity at 10° of incidence was about 68 per cent., and this gradually fell for increasing incidence, becoming about 64 per

[1] Read before the Royal Astronomical Society of Canada.

[2] "On the Power of Penetrating into Space by Telescopes, etc.," *Abridgment of Phil. Trans.*, **18**, 580, 1800.

[3] *Traité d'optique.* See Priestley's *History*, p. 540.

[4] *Edinb. Jour. Sci.*, N. S., **3**, 278, 1830.

[5] Newton, in a letter to the secretary of the Royal Society, dated May 4, 1672, discusses the advantages of his form of reflecting telescope over Cassegrain's, and remarks: "For it is an obvious observation that light is most copiously reflected from any substance when incident most obliquely."—*Abridgment of Phil. Trans.*, **1**, 712.

cent. at 60°. For a mirror of cast steel the same behavior was observed, the reflectivity falling from 59 per cent. at 10° to 54 per cent. at 60°. He thus concluded that the metals reflect better at small incidences. Subsequent investigations fail to substantiate the general law enunciated by Potter.

J. Jamin[1] worked with polarized light and compared the amounts reflected from silver, steel, and speculum metal with that from glass; and, assuming the laws of reflection from glass to be accurately represented by Fresnel's formulæ, he calculated the absolute amount of light reflected from the metals at various incidences. Jamin's results to a certain extent corroborate Potter's, but the agreement is not very good. Moreover, Jamin's indirect method has been criticised by Verdet[2] as not susceptible of great accuracy. About the same time the reflectivities of metals for heat-waves were studied by de la Provostaye and Desains,[3] and the values given by them for heat-waves are approximately the same as Jamin's for light-waves.

Sir J. Conroy[4] made an extended series of experiments on metallic reflection. He used a modified form of Ritchie's photometer, in which the light falls on the receiving screens obliquely, and thus polarization effects may have influenced the results to some extent. His mirrors were of silver, steel, tin, and speculum metal. With the first three the amount of reflected light gradually increased with increasing incidence, but with speculum metal it first increased, then diminished, and then increased again. These results are at variance with Potter's, Jamin's, and the theoretical formulæ deduced by Cauchy and MacCullagh.[5]

Rayleigh[6] measured the reflectivity of silvered glass and mercury for almost perpendicular incidence. For plate glass silvered on the anterior surface the reflectivity was 93.9 per cent.; when silvered on the posterior surface, 82.8 per cent.; for mercury, 75.3 per cent.

[1] *Ann. de Chim. et de Phys.*, (3) **19**, 296, 1847.

[2] *Leçons d'optique physique*, **2** (*Œuvres*, Tome **6**), p. 546.

[3] *Ann. de Chim.*, (3) **27**, 109, 1849; (3) **30**, 159, 276, 1850.

[4] *Proc. R. S.*, **28**, 242, 1879; **31**, 486, 1881; **35**, 26, 1883; **36**, 186, 1883; **37**, 36, 1884.

[5] See Verdet, *l. c.*, pp. 563 f.

[6] *Scientific Papers*, **2**, 522, 1886; **4**, 3, 1892.

The most extensive investigations on metallic reflection, however, have been recently made by Hagen and Rubens.[1] They measured the reflectivities for perpendicular incidence of numerous metals and alloys for wave-lengths ranging from 250 to 1500 $\mu\mu$; and the general conclusion was that the reflectivity increased with the wave-length.

Work similar to this and leading to the same result has been done by Rubens, Langley, Nichols, and Trowbridge.[2]

In two still later researches Hagen and Rubens[3] have shown that for long heat-waves the amount of the radiation entering the reflecting metal (i. e., the incident light less the reflected light) and the emissive power are inversely proportional to the square root of the electrical conductivity, and also inversely proportional to the square root of the wave-length of the incident radiation. This is in accord with Maxwell's electromagnetic theory.

II. REFLECTION FROM GLASS

Potter[4] was one of the earliest workers in this field also. He experimented with crown, plate, and flint glass, determining the reflectivity of the front face and also of both faces of a plate for incidences ranging from 10° to 85°.

Since Potter's time measurements have been made by many experimenters, usually in verification of the theoretical formulæ given by Fresnel.[5]

Rayleigh[6] measured the intensity of the light reflected at nearly perpendicular incidence from three specimens of glass, and concluded that recently polished glass surfaces have a reflectivity agreeing closely with Fresnel's formula, but that after some months or years it may fall off as much as 30 per cent. without any apparent tarnish on the surface. Some years later he measured the reflec-

[1] *Ann. der Phys.*, **1**, 352, 1900; **8**, 1, 1902.

[2] H. Rubens, *Wied. Ann.*, **37**, 249, 1889. E. F. Nichols, *ibid.*, **60**, 401, 1897; *Phys. Rev.*, **4**, 297, 1897. S. P. Langley, *Phil. Mag.*, **27**, 10, 1889; *Am. Jour. Sci.*, (3) **36**, 397–410, 1888. Rubens and Nichols, *Wied. Ann.*, **60**, 418, 1897. A. Trowbridge, *ibid.*, **65**, 595, 1898.

[3] *Ann. der Phys.*, **11**, 873, 1903; *Ann. de Chim. et de Phys.*, (8) **2**, 441, 1904.

[4] *Edinb. Jour. Sci.*, N. S., **4**, 53, 1831.

[5] See Verdet, *l. c.*, pp. 395–518. [6] *Scientific Papers*, **2**, 522, 1886.

tivity of water for nearly perpendicular incidence. He used a photographic method and found the value 2.076 per cent.

Conroy[1] has also studied the amount of light reflected and transmitted by certain kinds of glass. He used three kinds, having indices (for sodium light) of 1.5145, 1.5274, 1.6330, and worked with natural light. He showed that the amount of light reflected depends to some extent on the way the glass has been polished, and that the variation from the amounts calculated by Fresnel's formulæ is sometimes an excess, sometimes a defect. He found, too, that the surface of flint glass, after repolishing, seems to alter somewhat readily; while with crown glass the change, if any, proceeds very slowly.

A renewed interest has been given to the subject by the publication of Lord Kelvin's *Baltimore Lectures*, an entire long lecture, pages 324–407, being devoted to reflection. He remarks that very few experimenters have determined the proportion of the whole reflected to the whole incident light, and says that it is greatly to be desired that thorough investigation of this kind should be made. The present writer hopes to continue his experiments and thus contribute to this desired result.

III. METHOD OF EXPERIMENTING

The present investigation was undertaken through a suggestion made some time ago by Mr. J. R. Collins, secretary of the R. A. S. C. Mr. Collins and his brother, Mr. Z. M. Collins, designed, and in the year 1896 constructed, an achromatic telescope of 11.25 cm (4.5 inches) aperture, in which the light first passed through a double-convex objective of plate glass and then fell on a concavo-convex lens, also of plate glass, silvered on the back. Being reflected by this silvered surface, the light was returned to a small reflector, or, preferably, a total-reflecting lens-prism, near the posterior face of the objective, and thence into the eyepiece. (See Fig. 1.)

The focal length was 120 cm (48 inches), and the tube was 60 cm (24 inches) long.[2]

[1] *Phil. Trans.*, **180** A, 245, 1889.

[2] See *Trans. Astron. and Phys. Soc.*, Toronto, 1897, p. 23; *Toronto Astron. Soc.* 1900, p. 30; *Knowledge*, **23**, 252, 1900.

A somewhat similar arrangement is described by Schupmann in his work, *Die Medial-Fernrohre*, Leipzig, 1899, though all the figures in it call for two kinds of glass, crown and flint.

It was in discussing the efficiency of such a combination, involving reflection internally at a silvered glass surface, that the present investigation originated.

The method employed in it has, I believe, advantages over those previously used.

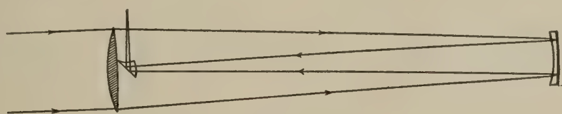

FIG. 1

A (Fig. 2) is a carriage moving on the ordinary photometric bench and bearing a Hefner standard lamp, *L*. *B* is another carriage. On this is a wooden arm *CD* which can revolve about a vertical axis through the center of the carriage. Just above this arm is a graduated brass disk *E*, rigidly fastened to the carriage. A pointer on the arm *CD* allows its position with respect to the disk to be read, and when the arm is parallel to the rails of the bench the reading is zero. A

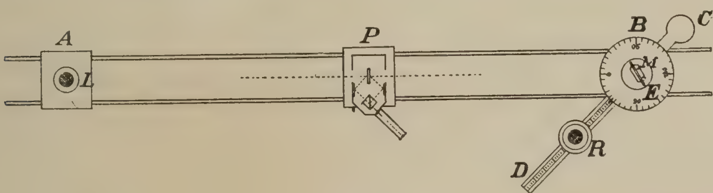

FIG. 2

second Hefner lamp *R* held in a turned wooden block can be slid along the arm *CD*, and a scale on this arm allows the distance of the axis of the lamp from the center of the graduated disk *E* to be read off directly. A small round table at the center of the disk *E* carries the mirror to be tested. This table can turn about the axis of the disk, and the mirror *M* is held between two metal strips so that the reflecting surface is at the center of the table. *P* is a Lummer-Brodhun photometer, the one used in these experiments being by Schmidt & Haensch, and arranged for equality of contrast.

It was necessary that the two lamps *R*, *L* should remain constant over an extended set of readings, and to this end cylindrical glass chimneys were placed over the flames, with a piece of fine wire gauze over the top and another over the bottom of the chimney. This

answered admirably, the flame being entirely unaffected by air currents.[1] In order to render the law of inverse squares more rigorously applicable, the glass chimneys were covered with black paper in which was made an aperture 1 cm high opposite the middle portion of the flame (Fig. 3). This flame was approximately of the height required for the standard lamp, but no attempt was made to have it accurately so, nor to have the two lamps accurately equal to each other. The only requisite was that the ratio of one to the other should remain constant.

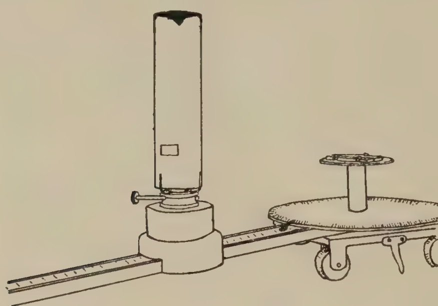

FIG. 3

When working with a glass surface, of which the reflectivity is small, the aperture in the black paper about the left lamp had to be reduced in size. It may be remarked, too, that the photometric bench had black velvet hangings all about it, except where the observer was working.

The method of operation was as follows: First the arm CD was turned to zero on the disk E, and the lamps R, L turned so that the photometer was exposed to their flames, the positions of the carriages A and B and of the lamp R on the arm being carefully observed. The photometer P was then moved until equally illuminated by the two lamps, and its position noted. This adjustment was usually repeated five or six times, and the mean taken. The distances thus obtained give the ratio between the two lamps. Then the arm CD was turned through twice the desired angle of incidence, and the lamp R turned about until its aperture was toward the mirror M. P was then moved until equilibrium was obtained between the light received directly from L and that received from R by reflection at M. This adjustment was made from four to seven times, and the mean taken.

In obtaining the ratio between the two lamps, let the distances of L and R from P be a, b respectively.

Then

$$L/R=(a/b)^2.$$

[1] For this expedient, and also for some preliminary experiments, I am indebted to Miss L. B. Johnson, B.A., and Mr. W. H. Day, B.A., senior students at the time.

Again, let equilibrium be obtained when the distances from L to P, P to M, M to R are c, e, f, respectively.

Then if x be the reflectivity, we have the relation

$$x=\left(\frac{a}{b}\times\frac{e+f}{c}\right)^2\times 100 \text{ per cent.}$$

The calculations were made by this formula.

The ratio between the two lamps was found at the beginning, the end, and usually also at the middle of a series of readings.

IV. RESULTS

Table I illustrates the method. It was obtained with Mirror II*a*, plate glass silvered on the front surface. The left lamp was at 70 cm to the left of zero; the right carriage at 120 cm to the right of zero;

TABLE I

MIRROR II*a*, SILVER IN FRONT

Readings of Position of Photometer

Ratio of Lamps	Reading on Arm	Angle of Incidence					
		5°	10°	20°	40°	60°	80°
At Beginning	$20=f$	35.04	35.20	35.15	35.34	35.00	34.80
		35.25	35.15	35.26	35.50	35.10	35.04
14.72		35.42	35.05	35.42	35.48	35.20	34.90
14.76		35.30	35.24	35.50	35 46	35.32	34.80
14.68							
14.58	Mean	35.252	35.160	35.332	35.445	35.155	34.885
14.680	Hence $c=$	105.252	105.160	105.332	105.445	105.155	104.885
	$e=$	84.748	84.840	84.668	84.555	84.845	85.115
At End	$30=f$	40.30	40.62	40.52	40.12	40.34	39.80
		40.28	40.70	40.26	40.26	40.28	40.08
14.25		40.40	40.70	40.32	40.36	40.30	40.22
14.25		40.26	40.62	40.40	40.60	40.30	40.30
14.60							
14.28	Mean	40.310	40.660	40.375	40.335	40.305	40.100
14.345	Hence $c=$	110.310	110.660	110.375	110.335	110.305	110.100
	$e=$	79.690	79.340	79.625	79.665	79.695	79.900
		45.10	45.40	45.62	46.18	45.88	45.68
Mean, 14.5125;		45.60	45.62	45.78	45.94	45.90	45.60
and $f=20$		45.22	45.72	46.00	46.08	45.70	45.60
Hence		45.32	45.52	45.80	46.18	45.60	45.54
$a=84.5125$							
$b=85.4875$	Mean	45.310	45.565	45.800	46.095	45.770	45.605
	Hence $c=$	115.310	115.565	115.800	116.095	115.770	115.605
	$e=$	74.690	74.335	74.200	73.905	74.230	74.395

and the numbers in the table give the positions of the photometer to the right of zero. From these readings a, b, c, e, f are at once deduced.

TABLE II

REFLECTIVITIES OF MIRRORS FOR ANGLES OF INCIDENCE FROM 5° TO 80°

Mirror	Angle of Incidence						Remarks
	5°	10°	20°	40°	60°	80°	
I*a*. Silver before glass....	95.62	95.84	95.45	96.07	96.44	95.94	Fresh mirror
II*a*. Silver before glass....	96.71	96.13	95.99	96.57	96.32	97.08	Fresh mirror
III*a*. Silver before glass, thick film...........	95.56	95.14	94.41	94.61	94.93	95.10	Fresh mirror
Mean	95.96	95.70	95.30	95.75	95.90	96.04	
III*a*. Silver before glass....	68.39	69.34	69.66	69.17	68.11	....	3 months old
I*b*. Silver behind glass...	87.40	87.42	87.17	87.65	87.59	86.69	Fresh mirror
II*b*. Silver behind glass...	90.84	90.75	90.64	90.05	88.14	83.24	Fresh mirror
III*b*. Silver behind glass...	90.88	90.77	90.58	90.03	88.41	80.76	Fresh mirror
Mean	89.70	89.65	89.46	89.24	88.05	83.56	
III*b*. Silver behind glass...	88.19	87.35	86.35	87.33	87.35	.....	3 months old
IV. Commercial mirror...	86.75	85.99	85.62	85.69	86.16	92.39	3 years old
V. Plate glass, one face..	3.98	4.08	4.20	4.70	9.33	40.90	Plate "backed"
	4.25	4.25	4.27	4.70	9.17	39.07	Calculated
VI. Flint glass...........	5.37	5.39	5.48	6.29	10.46	40.80	
	5.59	5.59	5.62	6.23	10.82	40.40	Calculated
VII. Dense flint..........	6.82	7.02	7.11	7.79	12.40	42.21	
	7.10	7.10	7.13	7.77	12.42	41.38	Calculated
VIII. Glass plate, both faces.	7.68	7.66	7.70	8.82	15.76	59.84	Same plate as V.
IX. Silver plate..........	66.09	65.34	65.28	65.25	66.01	72.34	Inferior polish
		[70.05	70.06	70.87	74.19	81.19	Conroy]
X. Speculum metal......	57.23	57.99	58.08	57.39	58.24	65.24	Inferior polish
		[66.13	66.88	67.26	66.32	70.17	Conroy]
		[67.26					Herschel]
		[67.52					Potter]

In Table II are given the final measurements made with the various mirrors.

I*a*, I*b*, denote the same mirror with faces reversed; similarly with II*a*, II*b*; III*a*, III*b*. These three mirrors were about 6 mm thick, and were silvered by Brashear. The following notes were made on them before testing their reflectivities:

I. Of ordinary density for a speculum, and with silvering as perfect as could be. Glass surface a little scratched, and not polished as highly as possible.

II. Not quite so dense as I, but silvering equally good. Reflected

white light rather better, i. e., without the reddish tinge due to the rouge used in polishing. Glass side polished rather better than in I.

III. Doubly silvered; film much thicker. Polish of silver surface not quite equal to the others. Showed slight rouge tint. Glass surface as in II.

The other reflectors were as follows:

IV. Commercial mirror, 2.8 mm thick, and at least three years old. Before using, its face was cleaned and rubbed with rouge on chamois.

V. Plate glass 2.8 mm thick and of refractive index 1.5193 (sodium light). Face rubbed with chamois. To avoid reflection from the posterior surface, this surface was coated thickly with the preparation used for "backing" photographic plates. This answered admirably. When a candle flame was observed in the plate not a trace of a second image could be seen.

VI. Flint glass, one face of a prism of refractive index 1.6194. The other faces were blackened.

VII. Dense flint, one face of a prism from a spectroscope by Lütz, and described as very dense white flint. The face was tarnished and had to be repolished. The refractive index was 1.7265.

VIII. Glass plate; the same as V without backing.

IX. Silver plate, of jewe[illegible] "pure silver." The polish was not very good.

X. Speculum metal; a fl[illegible]irror by Brashear, but having become tarnished, was repolished, though not very well, as the low reflectivity indicates. The measures taken, however, show what variation in the reflectivity there is with the incidence.

The calculated results given were obtained by substituting in the Fresnel formula

$$\frac{1}{2}\left[\frac{\sin^2(i-r)}{\sin^2(i+r)}+\frac{\tan^2(i-r)}{\tan^2(i+r)}\right].$$

The results in Table II are shown graphically in the curves of Fig. 4.

It would appear from the table that with the mirrors I*b*, II*b*, III*b* (silver behind glass), the reflectivities are smaller for 60° and 80° than for the lower incidences. This anomaly is undoubtedly due to the multiple reflection within the thick plate, for which it is

impossible properly to allow. With the commercial mirror, which was not half as thick, this effect is not observable.

Though the reflectivity of silver behind glass is about 6 per cent. smaller than that of silver before glass, this disadvantage is much

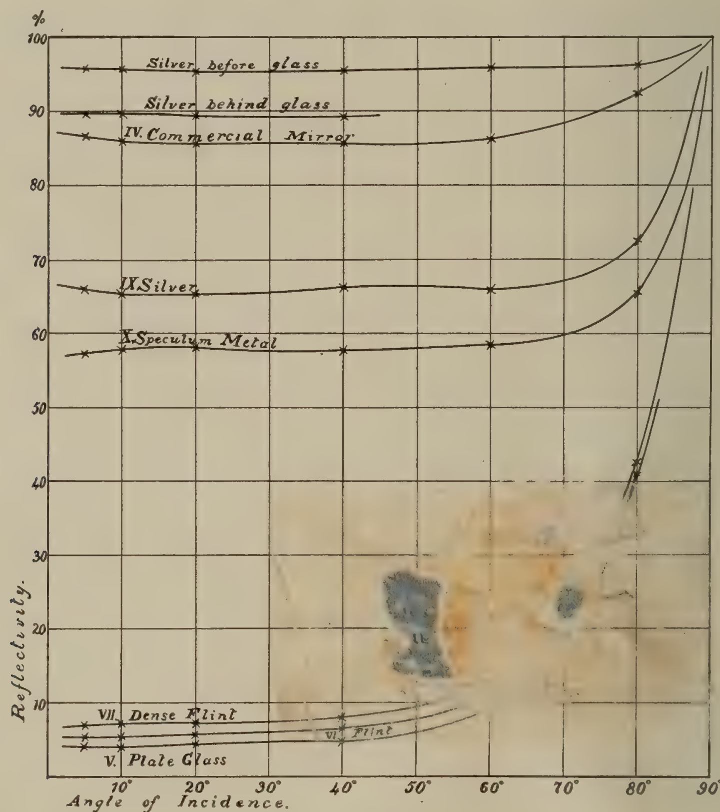

FIG. 4

more than balanced by the permanence of the former. After three months the mirror III had become so tarnished that as III*a* it fell from 96 per cent. to 68 per cent. but as III*b* it fell only from 91 per cent. to 88 per cent.; and ordinary commercial mirror at least three years old was at 86.7 per cent.

It will be interesting to determine the internal reflectivity of glass and of silver-on-glass. This may be calculated in the following way:

Let I (Fig. 5) be the intensity of light incident on a glass plate at A. A portion R is reflected and $(I-R)$ enters. Suppose that while traveling from A to B this is reduced by absorption to $(I-R)s$. If now the internal reflectivity be r, the part reflected at B is equal to $(I-R)\ sr$. By the time this reflected portion arrives at C it has been reduced by absorption to $(I-R)s^2r$. The portion of this which is reflected at C is $(I-R)s^2r^2$; and so on.

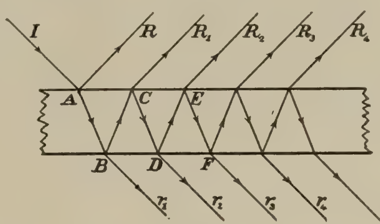

Fig. 5

Then

$$R_1=(I-R)rs^2(1-r)\,,$$
$$R_2=(I-R)r^3s^4(1-r)\ ;\ \text{etc.}$$

Hence

$$R_1+R_2+R_3+\ .\ .\ .\ .=(I-R)rs^2(1-r)\left[1+r^2s^2+r^4s^4+\ .\ .\ .\ \right]$$
$$=(I-R)rs^2(1-r)\frac{1}{1-r^2s^2}\ .$$

Now for a plate 2.8 mm thick

$$I=100 \text{ per cent.},$$
$$\left.\begin{aligned} R&=\ \ 4 \text{ per cent.},\\ R_1 \ [illegible] &=7.7 \text{ per cent.}\end{aligned}\right\}\ \text{(see Table II)}$$

Hence [illegible] er with the [illegible] tions, as, e. g. [illegible] a, etc.

$$[illegible]\frac{[illegible]-r)}{[illegible]s^2}=\frac{3.7}{96} \qquad (1)$$

Again, Con[illegible] ight of mean refrangibility on traversing 1 cm of crown glass has its intensity reduced by 2.62 per cent.

Here the reduction by 1 cm of glass is from 1 to $\frac{97.38}{100}$, and the reduction by 0.28 cm of glass is from 1 to $\left(\frac{97.38}{100}\right)^{0.28}$; i. e.,

$$s=\left(\frac{97.38}{100}\right)^{0.28}=\frac{99.26}{100}\ .$$

Substituting this value of s in equation (1), and solving the quadratic in r thus obtained, we find

$$r=4.07 \text{ per cent.},$$

the value of the internal reflectivity of glass.

For a plate silvered on the back, let p be the internal reflectivity for silver-glass. Then, as before,

$$R_1=(I-R)s^2p(1-r),$$
$$R_2=(I-R)s^4p^2r(1-r),$$
$$R_3=(I-R)s^6p^3r^2(1-r), \text{ etc.}$$
$$R_1+R_2+R_3+\ldots\ldots=(I-R)(1-r)s^2p(1+s^2pr+s^4p^2r^2+\ldots\ldots)$$
$$=(I-R)(1-r)s^2p\frac{1}{1-s^2pr}\ .$$

Now

$$\left.\begin{aligned} R+R_1+R_2+R_3+\ldots &= 90 \text{ per cent.} \\ R &= 4 \text{ per cent.} \end{aligned}\right\} \text{(Table I)},$$

and

hence

$$\frac{(1-r)s^2p}{1-s^2pr}=\frac{86}{96}\ . \qquad (2)$$

Using the values deduced above, namely,

$$s=\frac{99.26}{100}\ , \qquad r=\frac{4.07}{100}\ ,$$

we find

$$p=0.913, \text{ or } 91.3 \text{ per cent.}$$

i. e., the internal reflectivity of silver-glass is 91.3 per cent.

A formula similar to that for the reflected light can be found for the portion transmitted through a glass plate,

$$r_1+r_2+r_3+\ldots\ldots=(I-R)s(1-r)(1+\text{[illegible]}\ldots)$$
$$=(I-R)s(1-r)\frac{1}{1-r^2s^2}\ ,$$

and on substituting in this expression the values for r and s determined above, we find

Transmitted light=91.5 per cent.

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SPECTRA FROM THE WEHNELT INTERRUPTER[1] II

By HARRY W. MORSE

In a previous paper under the same title[1] there were reported measurements of the spectra of a number of metals used as active points in an arrangement similar to the Wehnelt interrupter. Tables of wave-lengths and intensities were given, and comparison tables for the arc and condensed spark of the metal in each case.

The present paper contains: (1) Similar measurements on the spectra of copper, gold, cadmium, iron, palladium, and platinum, photographed under the same conditions as have been described in the previous paper. The measurements for iron and platinum are from the third-order spectrum, the others from the first-order spectrum of the grating employed. (2) A brief qualitative note on the spectra which contain lines of both the point used and the metal in solution. (3) A note of the bands found in the Wehnelt and their occurrence in the spectra of the same metals under other conditions. (4) General comparisons of certain lines from the spectra of this and the previous paper with the same lines produced under special experimental conditions, as, e. g., in the spark with inductance, in the arc in hydrogen, etc.

The examination of the more complex spectra has not led to so much of interest as has been found in the simpler ones. It has, however, seemed best to publish tables of at least a part of the lines, in the hope that further knowledge of these spectra may increase their value.

The large number of lines in the Wehnelt spectrum, compared with that in the ordinary condensed spark between copper terminals, is remarkable. Not only are all the lines usually found in the spark spectrum present, but also most of those found by Eder and Valenta by means of a very strong condensed transformer spark. Among lines especially remarkable in this way are $\lambda\lambda$ 3530.5, 4063.0, 4275.0 and 4509.5. These are lines produced when the energy of the spark is

[1] *Astrophysical Journal*, **19**, 162, 1904.

I

COPPER

(Fig. 1)

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3247.5	20 (10)	5	20	4378.5	— (1)	4	—
3274.0	20 (8)	20	30	4480.4	— (3)	4	3
3308.0	3 (7)	3	1	4509.5	— (4)	—	4
3337.5	— (4)	—	1	4531.0	— (2)	—	4
3416.0	— (1)	4	—	4587.0	— (8)	6	1
3530.5	— (3)	—	3	4651.5	2 (8)	8	50
3571.8	— (—)	—	1	4675.0	— (6)	3	—
3599.5	— (1)	—	5	4704.6	— (5)	—	5
3654.5	— (1)	3	—	4933.5	3 (4)	—	—
3685.0	2 (3)	—	—	5105.5	6 (8)	30	100
3688.5	— (—)	5	—	5153.5	5 (10)	25	30
3839.0	— (2)	—	1	5218.5	20 (10)	15	100
3860.8	— (2)	—	1	5293.0	3 (6)	2	4
4023.0	1 (4)	8	5	5454.1	— (1)	—	1
4063.0	— (7)	8	6	5536.0	15 (3)	20	—
4080.5	— (—)	8	—	5700.5	3 (6)	15	20
4249.5	— (3)	—	1	5782.2	5 (8)	20	50
4275.2	— (10)	6	20				

Spark—Between copper points.

Arc—Metal on carbon terminals.

Wehnelt—Copper wire in dilute hydrochloric acid.

The intensities in brackets are those of Eder and Valenta,[1] obtained with a heavy transformer discharge. They are given on a scale of 1 to 10.

great and the temperature apparently very high. King[2] states that very little difference was noticeable between the spectra from sparks of very different intensities under the conditions of his experiments. I do not find these spark lines in measurable intensity on any of my plates. A few lines belonging to the arc spectrum are not present in the Wehnelt in sufficient strength to be observed. Among these are λλ 3688.5, 4080.5. Aside from these, there are a number of lines present in both arc and spark, which are absent from the Wehnelt table. λλ 3416, 3654, 4675, 5536, are of this kind. The last is a very strong line in both spark and arc.

The lines of copper for which Kayser and Runge have found series relation of a simple sort are:

[1] *Wien. Akad. Denkschriften*, 1896.

[2] *Astrophysical Journal*, **20**, 21, 1904.

5218.5*d* }
5153.5 } Stronger in Wehnelt than in spark or arc.
4063.0*d* }
4023.0 } Stronger than in the spark. Weaker than in arc.
3688.5 }
3654.5 } Absent from Wehnelt.
3274.5 }
3247.0 } Strong in all three spectra.

(The doublets marked *d* are not resolved by the dispersion employed.)

These lines are evidently not proportionately affected by the change of experimental conditions.

A large proportion of the lines which are especially strong in the Wehnelt spectrum are lines usually characteristic of low temperatures. The lines λ 5218.5 and λ 5105.0 are strong in the flame spectrum, and a number of the other strong lines are characteristically strong in the spectrum of the spark passing to solutions of copper salts. It is especially remarkable in this connection that nearly all of the lines of the high-temperature transformer spark are also present and strong.

GOLD
(Fig. 2)

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3554.0	3	5	1	4315.5	5	—	10
3572.0	—	—	1	4364.5	—	6	—
3586.5	5	—	4	4437.0	3	4	5
3651.0	1	—	1	4488.5	4	4	10
3750.5	—	—	2	4608.0	3	3 ?	5
3795.8	1	—	2*b* ?	4792.5	25	30	100
3874.5	—	—	1	4811.5	5	4 ?	5
3898.0	10	5	30	4861.0*b* ?	—	—	2
3909.5	2	3	1	5064.5	5	5	3
b	..	..	band	5230.0	15	4	8
4016.0	5	—	1	5465.8	1	—	3
4041.0	..	5	3	5581.0	5	—	1
4053.0	3	—	—	5611.0	—	—	1
4065.5	15	10	30	5656.0	6	4	5
4084.5	2	5	2	5837.5	6	3	8
4242.0	2	5	2	5863.0	3	4	1

Spark—Between gold terminals.
Arc—Metal on carbon terminals.
Wehnelt—Gold wire in dilute hydrochloric acid.
The lines of impurities are those of lead and silver.

This spectrum of gold differs markedly from both the spark and the arc spectrum of the metal in the far greater number of its strong

lines and the corresponding contrast as compared with the rather weak, flat spectra characteristic of the other experimental conditions. Several new lines are noted, and distinct traces of an underlying band spectrum are visible. The lines at λλ 3898.0, 4065.5, and 4792.5 are very much stronger than any lines obtainable in arc or spark. Several spark lines are enhanced, and the lines λλ 4016.0 and 5581.0, and some others, are reduced. The Wehnelt spectrum is in many parts very like that of the spark, and not in the least like that of the arc, which contains only about half as many lines in intensity sufficient to be observable. Some of the lines on the Wehnelt are characteristic of the spark in its strongest and most condensed form.

A band of considerable strength runs from λ 3910.0 to λ 4016.0, and a weaker band is visible with head at λ 4861.0 in the Wehnelt spectrum.

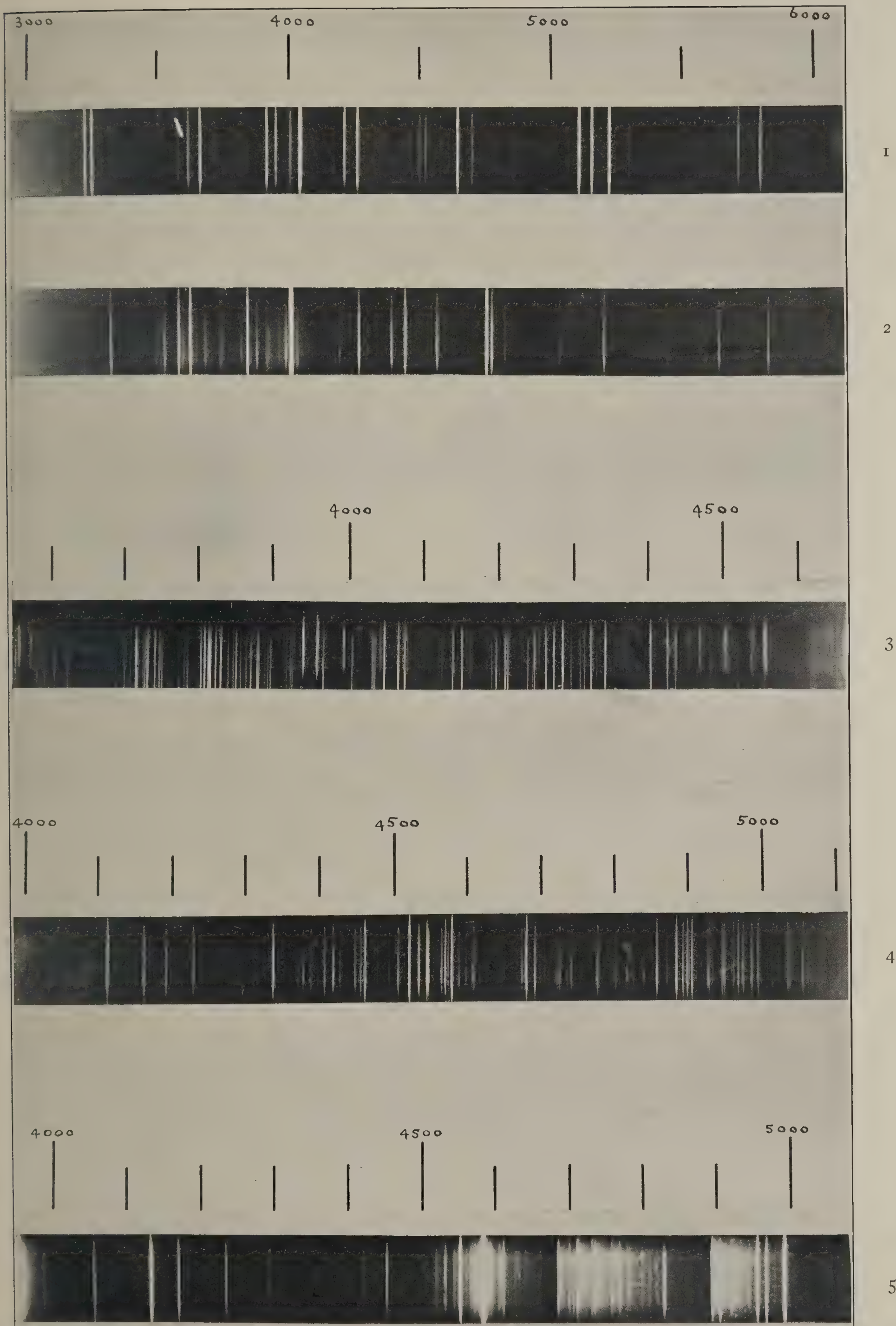
CADMIUM

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3250.5...........	10	15	3	4313.0...........	—	—	1
3261.0...........	25	20	8	4416.0...........	20	—	3
3403.5...........	30	20	25	4491.0...........	—	—	1
3467.0...........	50	30	40	4510.5...........	—	—	1
3610.5...........	50	30	50	4664.0...........	—	4	1
3734.0...........	—	—	1	4678.5...........	25	40	40
3776.5...........	—	—	1	4800.0...........	30	40	40
3822.5...........	—	—	1	5086.0...........	30	50	40
4102.0...........	—	—	1	5155.0...........	—	—	1
4122.5...........	—	—	1	5338.0...........	50*f*	—	3
4176.5...........	—	—	1	5348.5...........	—	—	1
4297.0...........	—	—	1	5379.0...........	50*f*	—	4

Spark—Between cadmium terminals.
Arc—Metal on carbon terminals.
Wehnelt—Cadmium wire in dilute hydrochloric acid.

The Wehnelt spectrum of cadmium is in many respects like those of zinc, tin, and lead. The pair of lines at λλ 5338.0 and 5379.0 belongs to the class already referred to under these metals as being strong, broad, and diffuse in the spark, absent from the arc, and sharpened and reduced in intensity in the Wehnelt. The line λ 4416.0 has these same peculiarities, while λλ 3250.5 and 3261.0 are present with nearly equal intensity in arc and spark, and are much reduced in the Wehnelt.

PLATE XIII



SPECTRA FROM WEHNELT INTERRUPTER

1. Copper point in hydrochloric acid. 2. Gold point in hydrochloric acid. 3. Iron point in hydrochloric acid (3d order spectrum). 4. Platinum point in hydrochloric acid (3d order). 5. Aluminum point in barium chloride solution (3d order).

IRON
(Plate XIII, Fig. 3)

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3872.6	4	8	6	4198.6*d*	6	10	12
3878.5	4	8	8	4202.2	6	10	10
3885.6	5	6	8	4210.3	3	5	3
3887.8	4	6	6	4219.4	3	5	4
3894.9	3	5	5	4222.3	2	5	2
3899.0	4	6	5	4224.2	1	3	1
3902.3	5	8	6	4225.5	1	4	1
3905.7	4	6	1	4227.6	3	10	8
3917.9	—	6	1	4233.7	3	10	7
3919.4	4	6	4	4236.0	4	10	10
3922.1	4	8	4	4238.8	2	5	2
3928.1	4	8	6	4245.4	1	4	1
3930.3	4	8	6	4247.5	2	5	3
3933.5	—	6	1	4250.8*d*	6	10	10
3956.7	3	6	2	4260.6	12	10	8
3966.5	3	5	2	4271.8	12	10	12
3969.4	6	8	10	4282.5	4	8	5
3973.2	—	4	1	4294.2	4	8	6
3977.7	3	7	1	4299.4	4	8	7
3997.6	3	6	3	4307.9*d*	15	10	12
4005.4	6	7	10	4315.2	3	10	5
4009.7	2	5	1	4326.0*t*	15	10	15
4014.2	2	5	1	4336.9	3	8	4
4021.9	2	5	2	4352.9	2	5	4
4030.9	—	5	10	4367.4	1	4	1
4033.2	—	5	8	4369.8	2	5	2
4034.5	—	5	7	4375.9	2	5	2
4041.3	—	5	5	4383.9	15	15	15
4045.8	15	15	30	4387.9	1	4	2
4055.4	—	5	1	4404.8	12	15	15
4063.7	10	20	30	4408.2*d*	2	4	2
4071.9	8	20	25	4415.2	10	10	12
4076.5	—	6	1	4422.3	1	5	2
4079.7	—	6	1	4427.3	2	5	2
4083.4	—	5	1	4430.3*d*	1	5	2
4084.8	—	6	1	4442.4	2	5	6
4107.4	2	6	2	4447.7	2	8	5
4109.8	2	8	2	4451.5	—	2	4
4118.7	3	10	5	4454.4	1	3	1
4127.6	—	5	1	4458.0	2	—	5
4132.2	5	10	10	4461.8	1	4	2
4134.6	2	10	5	4466.6	2	6	5
4144.0*d*	6	10	10	4469.3	2	4	2
4154.5	3	5	3	4476.0	2	8	6
4156.8	3	6	2	4482.2	3	4	5
4175.5	2	6	2	4494.6	2	4	8
4181.9	4	8	8	4528.8	3	6	10
4184.9	2	8	2	4547.9	—	4	2
4187.8*d*	4	10	10	4555.6	—	4	—
4191.5	3	10	4				

Spark—In air between iron points.

Arc—Metal on carbon terminals.

Wehnelt—Iron wire in dilute hydrochloric acid.

Wave-lengths of a number of weak lines are given in the Wehnelt column without note as to whether they are lines or maxima of bands. The position and general character of these maxima lead me to

PALLADIUM

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3243.0	10	20	20	4343.5	—	2	2
3251.5	6	10	25	4385.0	—	1	2
3259.0	8	10	10	4407.0	1	3	2
3267.5	6	5	8	4421.5	—	1	1
3279.0	—	—	8	4443.0	—	2	1
3287.5	3	5	5	4473.5	5	10	40
3302.5	15	15	40	4489.5	1	4	2
3373.0	10	15	25	4516.5	1	4	2
3383.0	1	10	10	4541.0	1	4	2
3405.0	30	20	50	4590.5	—	2	1
3421.5	15	10	8	4631.0	—	1	1
3430.0	1	2	5	4651.0	—	—	1
3433.5	10	10	10	4677.0	—	2	1
3441.5	10	10	8	4722.0	—	1	2
3446.0	—	—	8	4787.5	10	10	15
3451.5	10	—	—	4817.0	10	10	20
3461.0	15	10	15	4875.0	10	10	10
3481.5	20	10	20	4920.5	—	2	2
3490.0	10	10	15	4970.5	—	2	2
3517.0	20	10	20	5062.0	4	2	1
3553.0	30	8	20	5110.5*d*	10	5	5
3571.5	10	10	5	5163.0	15	10	15
3610.0	30	10	10	5209.0	5	3	1
3635.0	30	10	5	5215.0	—	—	1
3691.0	10	10	10	5234.0	10	8	3
3719.0	10	8	8	5256.0	5	2	1
3739.0	5	—	1	5294.0	15	10	20
3799.5	10	8	20	5309.5	5	2	1
3832.5	10	—	15	5342.0	5	2	1
3859.0	—	—	1	5361.5	5	2	2
3894.5	15	8	25	5394.0	10	2	6
3958.5	10	8	25	5431.5	—	—	1
4021.0	—	1	2	5462.5	—	—	1
4045.0	—	—	1	5495.0	—	—	1
4058.0	2	—	3	5524.0	—	—	1
4087.5	5	8	15	5542.0	10	10	50
4099.0	—	1	2	5589.5	—	—	3
4124.0	1	2	1	5606.5	1	4	4
4170.0	5	4	5	5629.0	—	2	2
4213.0	20	10	40	5640.0	5	3	1
4224.5	—	—	1	5668.5	8	10	30
4268.0	—	2	2	5694.0	8	8	15
4302.5	—	—	1	5736.5	5	5	5
4325.0	—	—	1				

Spark—Between palladium terminals.
Arc—Metal on carbon terminals.
Wehnelt—Palladium wire in dilute hydrochloric acid.

believe that they are bands similar to those found by Jones[1] in the spectrum of the vapor of cadmium in Geissler tubes. There are traces of a band from λ 4416.0 to λ 4491.0, and of another from λ 4297.0 to λ 4102.0, which correspond to bands found by Jones.

The plate shows the above region, photographed in the third-order spectrum. An aluminium spark was used merely to furnish a few lines for a starting-point in the measurements. The aluminium and air lines are visible, coming part way across the plate.

The Wehnelt spectrum of iron contains nearly all of the arc lines, many of them with greatly reduced intensities, and the whole appearance of the spectrum is like that of the arc, all of the lines being perfectly sharp and clear.

The groups λ 4030.9 – λ 4041.3, and λ 4076.5 – λ 4084.8, show how the spectrum resembles that of the arc, reduced in intensity. In other parts strong spark lines appear enhanced in the Wehnelt, but nowhere is it exactly similar to either of the other spectra over any considerable range.

The spectrum of palladium is an especially interesting one on account of its many strong lines, but there are no very marked differences between arc, spark, and Wehnelt spectra. Measurable differences of intensity occur everywhere, and there are a considerable number of lines which are strong in the spark, weaker in the arc, and weaker still in the Wehnelt. Examples are λλ 3635.0, 3739.0, 5256.0, 5309.0, and 5342.0. Occasionally a weak spark line appears enhanced in the Wehnelt, as λλ 3251.5, 3383.0, and 4473.5. I have been unable to find any relation between the appearance of the lines of palladium and their intensities in the different spectra. A considerable number of the lines of the spark spectrum are diffuse, and there are others which are diffuse in the arc. All of these are sharp in the Wehnelt.

The lines given for platinum are from a photograph in the third-order spectrum. There are many small differences of intensity, but none marked enough to offer any clue to the relation between spectra. All of the lines in the Wehnelt spectrum are perfectly sharp. There is no sign of a banded spectrum.

[1] *Wied. Ann.*, **62**, 30, 1897.

PLATINUM

(Plate XIII, Fig. 4)

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3900.7	5	5	8	4309.3	1	—	2
3904.3	1	2	3	4327.3	4	10	8
3911.0	3	2	2	4334.9	2	3	3
3923.2	15	3	15	4347.0	—	7	4
3948.6	3	6	2	4358.5	3	3	4
3966.6	7	12	10	4370.5	—	10	..
3996.7	3	—	2	4379.0	—	8	..
4066.5	—	3	3	4392.1	5	10	8
4081.7	3	2	4	4411.7	1	4	4
4092.5	3	3	4	4414.6	1	3	2
4119.0	10	10	15	4437.5	3	5	7
4164.8	7	6	10	4442.8	6	8	10
4192.7	6	6	10	4445.7	1	5	2
4201.3	1	2	2	4458.8	1	4	4
4227.5	1	4	..	4473.6	1	6	4
4251.2	1	1	1	4484.8	1	8	8
4260.2	1	—	1	4499.0	10	6	15
4263.8	1	2	2	4521.1	3	6	10
4288.2	2	5	2	4523.2	2	6	8
4291.0	1	2	1	4548.2	3	4	6
4302.6	2	—	3	4552.7	8	6	10

Spark—Between platinum terminals.
Arc—Metal on carbon terminals.
Wehnelt—Platinum wire in dilute hydrochloric acid.

II

It may be of interest to record the types of spectra produced when both the metal of the active point and the metal in solution in the electrolyte show lines. I shall give data for platinum, as that metal has been used under more varied conditions than any other. Qualitatively the results are as follows:

Platinum point in—

Hydrochloric acid	Only platinum lines
Sulphuric acid	Only platinum lines
Nitric-acid	Only platinum lines
Boric acid solution	Only platinum lines
Ammonium nitrate solution	Only platinum lines
Ammonium chloride solution	Only platinum lines
Lithium chloride solution	Platinum and lithium lines both strong
Potassium carbonate solution	Platinum and potassium lines both strong
Potassium chloride solution	Platinum and potassium lines both strong
Calcium chloride solution	Platinum lines weak; calcium lines strong

Strontium chloride solution	Platinum lines weak; strontium lines strong
Barium chloride solution	Barium lines only
Aluminium nitrate solution	Lines of both platinum and aluminium about equally strong
Mercuric nitrate solution	Platinum lines weak; mercury lines strong
Zinc chloride solution	Platinum lines quite strong; zinc lines strong
Zinc bromide solution	Platinum lines quite strong; zinc lines strong
Manganese sulphate solution	Platinum lines weak; manganese lines strong

Aluminium, when used as active electrode in almost any salt solution, shows its lines strongly (see Fig. 5). The plate chosen shows how the lines of the point and those of the metal in solution combine into a composite spectrum, without their relative intensities being in any way changed.

As has been stated in the first paper of this title, the condition favorable to the "Zerstäubung" of a platinum point and that favorable to a bright luminescence differ only slightly. It is evident that the point is furnishing glowing metallic vapor while the action is going on, and that the spectrum from this may, under some circumstances, be as strong as that from the metal left as vapor by the evaporation and dissociation of the water of the solution. Where the metal of the point is volatile only at a very high temperature (e. g., platinum) it might be expected that the spectrum of the released metal from the kation would predominate. In many cases, however, the platinum lines are as strong as those from the dissolved substance.

III

The metals which show especially remarkable bands in their Wehnelt spectra are zinc, tin, cadmium, and gold. On working over the literature of these metals with greater care, it seems evident that the bands noted for all of these except gold have been previously observed under special experimental conditions.

Zinc.—Bands of zinc were measured by Jones,[1] who gives maxima at λλ 4302.0, 4260.0, and 4240.0, tailing off toward the violet. The approximate wave-lengths of the maxima in the Wehnelt spectrum were given as λλ 4299.0, 4257.0, and 4238.0, and it seems probable that the bands are the same. Professor A. Fowler has kindly called my attention to his measurements of bands produced in the zinc arc

[1] *Wied. Ann.*, **62**, 30, 1897.

at very low pressures,[1] and here also it seems evident that the structure is the same.

Tin.—The reproduction given by Basquin[2] of the spectrum of the tin arc in hydrogen shows lines which closely coincide with the maxima given under this metal in the previous paper on the Wehnelt. The following lines are clearly visible in the reproduction:

	Spark	Arc	Wehnelt
4512	absent	absent	present
4525	present	present	present
4585	present	present	present
4617	absent	absent	present
4720	absent	absent	present
4810	absent	absent	present

The line at λ 4058 is apparently a lead line.

The lines λλ 4512, 4617, 4720, 4810 are evidently new lines of tin which appear under these conditions, although Basquin seems not to have recognized them as such. The Wehnelt spectrum contains, besides these maxima, which are evidently sharp lines, a considerable banded spectra in the violet.

Cadmium.—As has already been stated, Jones found the bands at λλ 4415.0–4494.0 and λλ 3990.0–4299.0 in the spectrum of cadmium vapor in Geissler tubes. The heads of these bands appear to be present on my own plates of cadmium in the Wehnelt, but as very weak maxima.

IV

The following table contains qualitative remarks on the intensity and appearance of certain lines under the following conditions:

1. Condensed spark.
2. Arc; metal on carbon electrodes.
3. Condensed spark with self-inductance in the secondary circuit.
4. Metal as point in the Wehnelt arrangement. (In the case of mercury the data are for a platinum point in a solution of a mercury salt.)
5. Arc under water
6. Arc in hydrogen.
7. Arc between metallic terminals.
8. Data from Schenck's analysis of the spark.

[1] *Proc. R. S.*, **72**, 253, 1903. [2] *Astrophysical Journal*, **14**, 1, 1901.

Data for the table have been taken from the papers of the following:

Inductance: Hemsalech, *Journal de Physique*, **8**, 653, 1899.
Inductance: King, *Astrophysical Journal*, **19**, 225, 1904.
Hydrogen: Crew, *ibid.*, **12**, 167, 1900.
Hydrogen: Basquin, *ibid.*, **14**, 1, 1901.
Various gases: Porter, *ibid.*, **15**, 274, 1902.
Under water: Hartmann and Eberhard, *ibid.*, **17**, 229, 1903.
Arc: metallic terminals: Hartmann, *ibid.*, **17**, 270, 1903.
Mercury: Huff, *ibid.*, **12**, 103, 1900.
Analysis of spark: Schenck, *ibid.*, **14**, 115, 1901.

Data for some of the lines under some conditions are lacking. These spaces have been left blank in the table. Where a line is absent from a spectrum the fact is noted by the word "absent."

Metal Line	1 Spark	2 Arc	3 Spark with Inductance	4 Wehnelt	5 Arc under Water	6 Arc in Hydrogen	7 Arc Between Metal Points	8 Schenck's Group
Magnesium—								
4481.0	str.[1] diff.	abs.	red'c'd sharp	red'c'd sharp	str. sharp	enh.	pres.	"B"
Zinc—								
4911.5 / 4924.0	str. diff.	abs.	red'c'd	red'c'd	str.		pres.	"B"
4058.0	abs.	str.	enh.	enh.				
Cadmium—								
4416.0	str.		red'c'd	red'c'd	str.			"B"
4678.0	str.	str.		str.				"A"
5339.0 / 5379.0	str. diff.	abs.	red'c'd sharp	red'c'd sharp	str. sharp			"B"
Tin—								
3351.0 / 3282.0	str. diff.	abs.		red'c'd sharp		enh.		
Lead—								
4062.0	abs.	str.	enh.	red'c'd				
4168.0	diff.	pres.	enh.	red'c'd				
4245.0	diff.	abs.	red'c'd	red'c'd			pres.	
4387.0	diff.	abs.	red'c'd	red'c'd				
5373.0	diff.	abs.	red'c'd	red c'd				
5547.0	diff.	abs.	red'c'd	red'c'd				
5608.0	diff.	abs.	red'c'd	red'c'd				
Mercury—								
3663.0	pres.	pres.	enh.	enh.				
3665.0	pres.	pres.	enh.	enh.				
4078.0	pres.	pres.	enh.	enh.				
4916.0	pres.	pres.	enh.	enh.				
5426.0	pres.	abs.	red'c'd	red'c'd				

As will be clearly seen in the table, the Wehnelt spectrum (with a few exceptions, as *Pb* λλ 4062.0 and 4168.0) is very much like the

[1] Str. = strong, diff. = diffuse, abs. = absent, pres. = present, enh. = enhanced.

spark spectrum with inductance in the secondary circuit. The strong diffuse lines of the spark are reduced and sharpened by the introduction of inductance, and the same effect is a general one in the same lines in the Wehnelt. The zinc line λ 4058.0, which is absent from, or very weak in, the spark, is greatly enhanced by inductance and is a strong line in the Wehnelt. In the spectrum of mercury the changes in intensity from spark to spark with inductance and those from spark to Wehnelt are closely parallel.

Several other metals not given in the table show similar changes. The aluminium lines $\lambda\lambda$ 3613.0 and 3602.0 are cut out from the spark spectrum by the addition of inductance, and they are also greatly reduced in the Wehnelt. The silver lines $\lambda\lambda$ 4668.5 and 4055.5 are enhanced by inductance and stronger in the Wehnelt than in the spark, and many other lines follow the same course of changes.

All of the lines which show striking changes in appearance and intensity under the various experimental conditions are *non-series* lines, and most of them belong to Schenck's class B, of which magnesium λ 4481.0 may be taken as a prototype. These are the lines which are, as a rule, reduced or cut out of the spark spectrum by the addition of inductance, and they are usually the lines which are enhanced in hydrogen or under water. To this class belong lines which are usually ascribed to the spark, but which appear in the arc between metallic electrodes when the current is made as small as possible.

These have been often called "high-temperature lines," but there seems to be no reason for assuming that the arc in hydrogen or under water is higher in temperature than that in air, nor is there any direct evidence that the introduction of inductance into the secondary discharge circuit decreases the actual temperature of the metallic vapor in the spark. Further analyses of the spark and Wehnelt discharges, by methods similar to those employed by Schuster and Hemsalech,[1] and Schenck,[2] should throw light on these important questions.

CONCLUSION

1. The spectra produced in an arrangement similar to the Wehnelt interrupter show well-marked differences from those belonging to the same metals as produced in the spark and the arc, both in the relative

[1] *Phil. Trans.*, 193, 189. [2] *Loc. cit.*

intensity of lines and in their appearance, but no definite *type* of spectrum appears to be characteristic of this method of spectrum production.

2. The variations in intensity between lines in spark spectra and the same lines in the Wehnelt arc closely parallel to the variations from spark to spark with inductance.

3. Lines belonging to the series of Kayser and Runge show little change in appearance or intensity under varying experimental conditions. This statement, which has been proved for other cases, may now be extended to include spectra produced in the Wehnelt interrupter.

4. Non-series lines show in many cases great variations in intensity and appearance under various conditions of spectrum production.

5. The evidence that the lines which show marked variations in intensity and appearance under various conditions are those corresponding to the highest temperature seems to be by no means conclusive.

6. The bands found in the Wehnelt spectra appear also under other experimental conditions, either in the arc in hydrogen, in the arc at very low pressures, or in the Geissler tube spectrum of the metal.

My especial thanks are due to Professor Langley for the loan of the large-aperture grating used in this work. Only by its use was it possible to photograph the normal spectra of these weak luminescences with exposures of reasonable length.

Jefferson Physical Laboratory,
Harvard University,
January 30, 1905.

SOME EMISSION SPECTRA OF METALS AS GIVEN BY AN ELECTRIC OVEN

By A. S. King[1]

Spectroscopic investigations with the electric arc and spark have furnished much evidence that when the current thus passes through the incandescent vapor, the vibrations producing spectral lines are strongly influenced by the electrical conditions then prevailing in the arc or spark. Thus in the spark spectra of many elements there are lines which never appear in the arc spectrum, and which a closer examination shows to be easily altered in intensity by slight changes in the spark discharge. Also in the arc many variations in the spectrum seem most probably due to differences in arc conditions. Concerning the actual nature of these electrical influences our knowledge has advanced but little; crucial tests seeming in many cases impossible, since the change of one condition directly affects numerous other conditions to an unknown extent.

Clearly the production of emission spectra with electrical action excluded would be most desirable; but a temperature must be produced not far below that of the arc, unless we are to be content with a few lines, such as are given in flame spectra. Attempts to produce spectra in tubes tested in furnaces were made by several early investigators, but the first really effective method seems to have been that used by Liveing and Dewar[2] in the course of their experiments on reversibility of lines, but which they found capable of producing numerous emission lines. The essential principle of this oven has been used by the writer in the work to be described. An arc is formed between a vertical carbon rod and a horizontal carbon bored out and containing the metal to be vaporized. The carbon tube becomes very hot just above the arc, and the spectrum of the vapor appears. The observations and photographs made by Liveing and Dewar showed the efficiency of the method, but, aside from a very few observations made by them, no use seems to have been made of the prin-

[1] Research Assistant of the Carnegie Institution of Washington.

[2] *Proc. R. S.*, **34**, 119, 1882.

ciple, and it certainly has not become a recognized working method in the attempt to bridge the gap between flame and arc.

The next work along this line was concerned largely with the question whether spectra can be produced by high temperature alone. This work, beginning with E. Pringsheim's[1] experiment with sodium in a heated porcelain tube, and followed by experiments by Paschen,[2] is reviewed at length by Kayser.[3] The difficult question as to the exclusion of all chemical action which might produce luminescence is the chief contention in these articles. The temperatures used were low compared to that of the arc.

With the subject in this stage, I took up the problem, at the suggestion of Professor Kayser, of developing a method for producing emission spectra in a tube heated by electricity as nearly as possible through the agency of heat alone. When a practical oven had been devised, the work of which the results are to be given was carried forward with the apparatus in its original crude form, leaving improvements in the oven for a second series of experiments.

When these results were almost ready for publication, a work by R. Nasini and F. Anderlini[4] appeared, which has the same general purpose as mine and was performed with an electric oven. Their apparatus is not sufficiently described to enable one to see whether it is at all similar to mine. Their chief experiment was the vaporization of magnesium in a graphite tube for the purpose of using up the oxygen of the air, and they thought that they observed the spectrum of nitrogen (?) under these conditions. My results for Mg, which is the only experiment parallel to theirs, will be given later.

APPARATUS

In the experiments to be described, two forms of oven were used; but as almost all the results so far have been obtained with one form, a description of this will be given first. It was a modification of the oven used by Liveing and Dewar, and the materials used were of the simplest sort. The figure gives a cross-section showing the arrange-

[1] *Wied. Ann.*, **45**, 428–459, 1892.

[2] *Ibid.*, **50**, 409–443, 1893; **51**, 1–39, 1894; **52**, 209–237, 1894.

[3] *Handbuch der Spectroscopie*, II, 150–157.

[4] *Rendic. Accad. dei Lincei*, (5) **13**, 59–66, 1904.

ment. Two carbon battery elements *b, b* were taken and a side of each hollowed out, so that, when placed together a cylindrical space about $2\frac{1}{2}$ cm in diameter was formed. An ordinary cored electric light carbon *c*, 16 mm in diameter, was bored out with a hole 5 mm in diameter, placed inside the cylinder formed by the two carbon blocks, and insulated from these by two tubes of abestos *a, a*, each reaching about 5 cm in from the end, thus leaving the middle part of the bored-out carbon free. In the middle of the lower carbon block a hole was bored, through which a carbon *d*, 12 mm in diameter was passed. Copper clamps on the ends of both horizontal and vertical

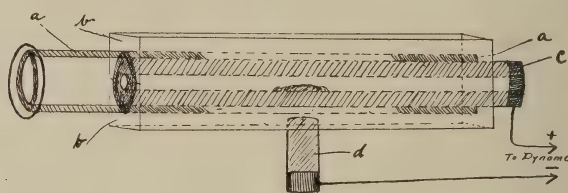


Fig. 1.

carbons connected with mercury cups, and in these were placed the terminals of a 220-volt dynamo circuit, the positive terminal to the horizontal carbon. Raising the vertical carbon then formed an arc between its end and the side of the horizontal carbon tube. With this voltage an arc of only 2 or 3 amperes could be used at first and increased slowly, as too rapid heating was liable to crack the carbon tube. This forms the essential part of the apparatus, but it was further protected by other battery carbons built up around it, which served to retain the heat and prevent oxidation of the two carbon blocks inclosing the tube, as these soon became red-hot.

This very simply constructed oven proved remarkably durable and effective. An arc of 30 amperes could be easily maintained, and the oven could be used daily for a month without any of the carbon blocks being renewed. The bored-out carbon, being the + terminal, became intensely hot, and in time would burn through, though maximum current could generally be used for half an hour and 15 to 20 amperes for a much longer time. The metal or salt whose spectrum was desired was placed in the tube directly over the arc, and further supplies could be pushed in by means of a small carbon

rod, while the spectrum was observed visually or photographed through the other end of the tube. Unless opaque vapors were given off in such quantities as to require an outlet, the tube could be made almost air-tight by letting the asbestos insulation at one end form an extension tube closed by a quartz window, while at the other end an asbestos plug was inserted in the carbon tube.

We have then an apparatus in which the substance to be vaporized is within the positive terminal of a very strong arc and separated not more than 5 mm from the arc itself. The inside of the tube becomes white-hot over a length of perhaps 5 cm, and strong emission spectra were readily obtained, from the carbon itself and metallic impurities as well as from a number of metals and salts placed in the tube directly above the arc.

After a few preliminary visual observations, the spectra thus given were studied entirely by photography, at first with a prism spectrograph in which the small glass prism used gave low dispersion, but very bright spectra; and later in as many cases as possible the spectra were photographed with a Rowland concave grating of 1 m radius, this requiring, however, much longer exposure. The narrowness of the carbon tube caused some continuous spectrum from the white-hot walls to appear, but the shortness of the incandescent portion made this continuous ground so weak as to give little trouble, even weak spectral lines appearing distinctly; and in order to eliminate the continuous spectrum as far as possible, a sharp image at the interior of the oven was projected by a quartz lens on the slit—an image so large that the ring formed by the incandescent walls did not appear on the slit. The spectrum lost somewhat in intensity thereby, but the continuous ground was rendered very weak, especially in the grating photographs.

For identification of lines and comparison with the arc lines, an arc spectrum was in most cases photographed beside the oven spectrum by placing an arc containing the metal behind the oven when the latter was not in action, so that the arc rays passed through the oven tube.

PROBABLE TEMPERATURE OF THE OVEN

Attempts to arrive at the approximate temperature of the oven were made by seeing what could be melted, and also by a thermopile

measurement. With the moderate current of 15 amperes, small pieces of quartz placed in the tube melted and fused together. When the arc current was raised to about 25 amperes, the quartz was not only melted, but rapidly vaporized, forming a thick white deposit inside the tube, in which could be seen tiny globules of sublimed quartz. As we have no idea of the temperature indicated by this, a thermopile measurement was made to find the maximum of radiation in the spectrum. Dr. Pflüger very kindly made this measurement for me with his fluorite apparatus and thermopile. It was, of course, possible to measure only the average radiation from the inside of the tube, but to come nearer to the temperature of the bottom, on which substances to be vaporized lie, the carbon was bored out only as far as the point above the arc, in order to obtain the radiation from the carbon direct, but still the temperature of the carbon doubtless falls off very rapidly as it recedes from the actual point of contact of the arc. The thermopile showed the maximum to lie between 1.6 and 1.5 μ, approaching the latter value as the time went on. Reducing the measurement to the normal spectrum of a black body, and calculating the temperature from Wien's equation, we obtain a value of about 2000° abs., assuming the radiation to be that of a black body. For several reasons it is clear that this must be regarded as a lower limit and not as the real temperature which produces the spectra: (1) The room in which the thermopile was mounted was not fitted with wires heavy enough to carry the high current for a sufficiently long time to give the temperature obtained when photographs were taken. With the maximum current that could be used, the energy-maximum moved steadily toward shorter waves. (2) The calculation considers that the inside of the tube acts as a black body, but this was only in part true, as the end toward the thermopile was not sufficiently closed; so that we obtain a mean value, and the upper part of the tube is necessarily much cooler than the bottom. (3) Quartz vaporizes. For these reasons it would seem safe to assume the temperature of the bottom of the tube as at least 2500° abs.

TRIAL OF A RESISTANCE OVEN

An oven of a different form was constructed and used sufficiently to demonstrate its efficiency. This was essentially a carbon tube heated by the passage of a strong electric current. A graphite tube

of 1 cm inside diameter and 20 cm long was copper-plated at the ends and laid horizontally with the ends on two supports made of thick copper wire, bent and flattened at the end to form a spoon, which made contact with the copper-covered end of the tube; the other end of the wire dipped in a mercury cup in which was also a terminal of a dynamo circuit. To avoid oxidation of the carbon when heated, the tube with its supports was placed in a box of asbestos powder and entirely covered with this, while observation of the interior was provided for by means of an asbestos tube fitting on one end of the carbon tube and passing outside the box, where it was closed by a quartz window.

The tubes at my disposal were of such low resistance that the available current of 50 to 60 amperes served to bring them to a high temperature only when the tube was oxidized enough to be quite thin, after which it lasted but a very short time. The chief observations with this oven were taken visually with metallic calcium in the tube, and the changes in the spectrum of this element will be spoken of later. As a means of obtaining a long column of uniformly heated vapor, with the tube of sufficient diameter to make the continuous spectrum weak, this form of oven is superior to that heated by the arc, and the spectra appear readily when the tube becomes white-hot.

As the materials were not available to use the resistance oven to the best advantage, I have devoted most of my attention in this first work to the oven heated by the arc. The spectra of the several elements studied will now be considered and the results given.

CÆSIUM

The three pairs of the principal series of cæsium were readily produced with the arc oven when cæsium sulphate was used in the tube. This element was investigated in some detail, with the special object of observing the effects of varying temperatures on the members of the principal series. Numerous photographs were made with the oven heated to different degrees by arcs of high and low current.

The photographs taken show clearly that *with rising temperature the series lines of shorter wave-length become relatively stronger*, i. e., for this vapor the maximum of radiation shifts toward ultra-violet. With an arc of 15 amperes a photograph was obtained with the prism

spectrograph in which the pairs λλ 4593, 4555 and λλ 3889, 3877 appeared, the latter very much the weaker. No trace of the third pair λλ 3617, 3612 was to be seen. With a current of 25 amperes the second pair was almost as strong as the first, which did not, however, appear to be overexposed, while the third pair could be faintly seen. Changing the current back to 15 amperes while the oven was still very hot from the trial with 25 amperes, a third photograph was obtained in which the last pair did not appear, but the difference in intensity between the first two pairs was much less than in the first photograph with this same current, the effect being clearly between those of the low and high currents. Other trials were made which confirmed these results, and then an attempt was made to get similar photographs with the small grating. Here a much longer exposure was needed, and the intensity fell off toward the violet much faster than with the prism. However, the effect is here distinctly visible. In the figure, Nos. 1 and 2, are the two photographs with 15 and 25 amperes respectively. The pair λλ 4593, 4555 are of almost exactly the same intensity in both, and are certainly not overexposed, as another plate was taken with longer exposure in which this pair was at least 50 per cent. stronger. The second pair, judged best by its strongest line, is fully twice as strong with 25 as with 15 amperes. The third pair is too weak to reproduce, but can be faintly seen in the negative taken with 25 amperes. The conclusion to be drawn from this result is that *an incandescent vapor follows the law of radiation of a solid body*, as judged by the shift of the maximum in the radiation from the particle which produces this series of lines.

Application to the relative temperature of arc and spark.—From photographs taken in a previous investigation, and others kindly placed at my disposal by Dr. Konen, I have made a comparison of the arc and spark spectra of several elements having lines in series, with reference to the falling off in intensity of series lines toward shorter wave-length. In several of these it is clearly to be seen that in the spark spectrum the members of a series fall off more rapidly in intensity toward shorter wave-length than in the arc spectrum. In the *Na* and *K* spectra this is to be observed in the first and second sub-series. With copper it is very pronounced in the first sub-series

the difference between the first two pairs being much greater in spark than in arc, and it is well known that the third pair, λλ 3688, 3654 does not appear at all in the spark. With calcium the effect is evident in the triplets of the first sub-series, and present, though less pronounced, in the first sub-series of *Mg*. In the spectra of *Cd*, *Zn*, *Hg*, and *Al*, I was unable to detect a difference of this kind, the decrease seeming about equal in arc and spark; and the first sub-series of *Li* seemed to offer an exception to the rule, though the

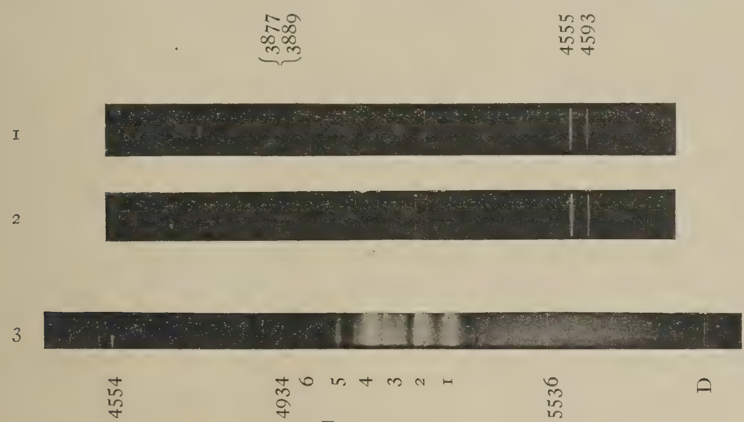


FIG. 2

EXPLANATION OF PHOTOGRAPHS

Nos. 1 and 2 show the two pairs of the cæsium spectrum, as given when the oven was heated by arcs of 25 and 15 amperes respectively. The head of the cyanogen band at λ 3883 appears between the lines of the lower pair.

No. 3 shows the barium spectrum given by the oven with a comparison arc spectrum superposed below. The three barium lines are shown which are discussed in the paper and also the structure of the green band-group.

uncertainty as to whether some of the *Li* lines are double or reversed makes it difficult to decide for this element.

This shift of maximum in the spark toward longer waves, in connection with the behavior of the cæsium series at different temperatures, would point, on its face, to the conclusion that the arc is of higher temperature than the spark, in contradiction to the view generally held; though our knowledge will not enable us to deny that most of the spark properties usually deduced as evidence of higher temperature, such as great brightness with small volume,

richness of spark spectra in ultra-violet lines, etc., may be the result of the more violent electrical action. However, the modern view points to something so different from a thermal radiation in the spark that it seems as if the word "temperature" cannot be used in the same sense for both arc and spark. The more rapid falling off of series lines toward shorter wave-length in the spark scarcely offers in itself enough evidence to offset that on the other side. In the first place, the effect seems not to be so general as we should expect, several exceptions being noted above; and, secondly, it is conceivable that the spark discharges may affect the vibrating particles so as to bring about a shift of the maximum radiation analogous to that given by a true thermal change. But if this is the basis of the behavior of series lines in arc and spark, we have the peculiar condition that the stronger electrical discharge of the spark acts in the same direction as *lower* temperature, shifting the maximum toward the red. Still, such a state is not impossible, as the phenomena of sound tell us that in some cases a more powerful stimulus may strengthen the lower members of a series of vibrations.

CALCIUM

1. *Visual observations of stronger lines.*

a) *With resistance oven.*—With metallic *Ca* in the graphite tube heated by a current, a few observations were made of the changes in the stronger *Ca* lines as the current rose. As the oven became hot, the D lines of sodium appeared, given by impurities in the carbon, then with higher temperature came lines in the red and green which were roughly identified as λλ 6439, 5594, 5589. With still higher temperature these lines broadened and λ 5858 appeared, then the two red lines λλ 6162, 6122. The *g* line, λ 4227, was not observed, though the spectroscope used was not favorable for visual observations in the violet. The group of lines thus obtained proved very sensitive to slight changes of temperature as governed by the current through the tube. A change of 2 or 3 amperes would cause an entirely different intensity relation among the several lines, giving a striking example of the slight change of conditions required to bring about large changes in the appearance of a spectrum.

b) *With arc oven.*—When metallic *Ca* was vaporized in the tube heated by an arc, a higher temperature was doubtless reached, and the development of the stronger lines could be again watched as the tube became hotter; and in this case the continuous spectrum given by the walls of the narrow tube produced frequent reversals. With no chemical in the tube, the trace of *Ca* in the carbon caused the red line λ 6439 to appear soon after the D lines. With metallic *Ca* in the tube the relation of emission and absorption for some of the stronger lines could be watched. At first the red *Ca* line and D appeared reversed, given by the glowing tube and the comparatively cool vapor. As the tube became hotter, D became bright, while with the *Ca* line absorption was balanced by emission and the line disappeared. *g* also appeared now. When a small carbon rod was inserted in the tube, giving a stronger background, all of the lines appeared reversed, to become bright again when the rod was withdrawn. When the tube became very hot, with a large quantity of vapor in it, only dark lines appeared, the strong lines in red, yellow, and green, which did not show before, appearing now also reversed. If at this stage the arc was broken, all the lines became bright almost instantly, and remained visible for varying lengths of time, those in the red and green for about 15 seconds.

2. *Photographic observations with arc oven.*

a) *Behavior of the H and K lines as compared to the g line.*—The photographs taken with the oven showed many differences from the arc spectrum, but among these the most interesting was the action of the lines $\lambda\lambda$ 3968, 3934 known as H and K. These lines, given strongly by all conditions of arc and spark, even when only a trace of *Ca* is present, appeared as bright lines in the spectrum given by my oven only under maximum conditions of temperature and vapor density, and then very faintly. With a large amount of metallic *Ca* in the tube, a long exposure and an arc current of 25 amperes, the H and K lines could be detected as very faint narrow lines, with the aid of a comparison arc spectrum. Under these conditions, *g* is overexposed and broadly reversed, the series triplets with lines of greater wave-length at 4455 and 3644 are very distinct, the first-named triplet being strong, as is also the group of six lines from λ 4319 to λ 4283. The non-series triplet beginning at 4586 is absent,

as is also the pair 3737, 3706, which has the same vibration difference as H and K, and is strong in the condensed spark. The higher temperature of the arc is probably in part responsible for this difference, but the magnitude of the change, as well as the action of H and K in spark spectra[1], where they are favored by the highly condensed spark and reduced relatively to *g* by self-induction in circuit, point to the electrical conditions in the arc and spark as being necessary to give these lines their usual intensity.

b) *Unsymmetrical reversal of the g line.*—The *g* line shows an apparent displacement in some grating photographs. In these the comparison arc spectrum usually gives *g* reversed, and in several cases where the oven spectrum gave *g* sharp it was seen to coincide with the edge rather than the middle of the reversed arc line. A measurement on one plate from the sharp line given by the oven to the middle of the reversed arc line gave a difference of 0.48 tenth-meter toward greater wave-length, the direction of apparent displacement being the same as for H and K. On this same plate numerous sharp lines were perfectly continuous in the two spectra. However, when the reversal of *g* was narrower, its apparent displacement was less, and on some plates when *g* was not reversed in the arc it appeared continuous with the sharp line of the oven. Thus the evidence favors considering the action of *g* as an unsymmetrical reversal.

c) *Reversal effects of Ca vapor.*—An experiment was tried with *Ca* which may be put to general use in the study of reversal phenomena, if the apparatus is so altered as to give a longer column of vapor. A large amount of *Ca* vapor was produced in the tube from the metal, and a carbon arc containing *Ca* was placed at the end of the oven so that its light should pass through the intensely heated vapor to the grating. The absorption possibility of *g* as compared with that of the other *Ca* lines was the most striking result of this trial. The low dispersion made it difficult to decide whether the lines other than *g* were reversed or not, but at any rate only *g* had its reversal increased by passage of the arc radiation through the vapor in the oven. The reversal of *g* was always wider than with the simple arc, and became broader as the vapor in the oven was

[1] A. S. King, *Astrophysical Journal* **19**, 225–238, 1904.

more intensely heated, reaching a width of several tenth-meters at maximum temperature of the oven. Probably the increased quantity of vapor and higher temperature worked together to give this result.

3. *Band spectrum of calcium.*—The well-known *Ca* bands in the orange and red, which appear sometimes in the arc, were very brilliant and constant with the oven. In addition to these, the oven gives a set of much weaker bands in the violet which I believe have not been previously observed. Five bands are visible in this group, and, while rather diffuse, appear to be shaded toward the red. These were obtained in grating photographs, and I have measured the positions of the strongest part of each band, as well as the definition would allow, as follows:

3691	faint, diffuse
3766	diffuse
3835	well-defined edge, shaded toward red
3892	well-defined edge, shaded toward red
3959	diffuse

These bands appear with the oven at moderate temperatures and with either metallic *Ca* or the chloride in the tube, strongest with the latter. This points to the oxide as a possible cause, air being present, though no careful tests have been made on this point as yet.

STRONTIUM

1. *Line spectrum.*—With strontium chloride in the oven, the spectrum is much less sensitive than that of calcium. However, some of the stronger lines were obtained and showed a relative intensity among themselves quite different from that in the arc. The lines λλ 4607, 4215, 4077 are considered homologous, from their position and general behavior, to the *Ca* lines *g*, H and K respectively; and the changes made by the oven are similar to those observed with the three *Ca* lines, though not so pronounced. λλ 4215 and 4077 are connected by the vibration difference 801.5, which occurs several times in the *Sr* spectrum. In the arc they are always strong, almost, if not quite, as strong as λ 4607. The oven, however, gives only the faintest traces of this pair, while λ 4607 is of considerable intensity, much the strongest line in the spectrum.

2. *Band spectrum.*—As with *Ca*, the oven serves to bring out a strong band spectrum. The bands in the orange were observed visually and were very strong. In addition, my photographs show a much weaker set of bands in the violet, which I believe are new. Four bands appear here, whose approximate wave-lengths and appearance are as follows:

3937	sharp edge, shaded toward red
3962	sharp edge, shaded toward red
3992	diffuse
4014	diffuse

The first two bands have very distinct edges toward the ultra-violet. No resolution into lines is given by the dispersion used, these bands evidently being of much denser structure than those in the orange.

BARIUM

1. *Line spectrum.*—Barium chloride was used in the oven, and here again the interest centers around three lines, λ 5536 and the pair $\lambda\lambda$ 4934, 4554, which were the only ones obtained in this region. The last two, a strong arc pair, are very faint, only a trace of λ 4934 being visible, while λ 5536 is strong. The ratio of intensities in oven and arc for λ 4554 is about 1:20, for λ 5536 about 3:4 (see Fig. 2, No. 3).

The lines $\lambda\lambda$ 4934, 4554 are shown by their behavior in the magnetic field[1] to be of the same type as $\lambda\lambda$ 4215, 4077 of *Sr*, and H and K of *Ca*. This homology is borne out by the action of the three pairs in the oven spectrum. These pairs, moreover, being of the same magnetic type as the D lines of *Na*, are considered as probably members of the principal series for their respective elements, the other members being as yet unknown. If this is the case, however, we have here an exception to the rule that principal series lines are given by the simplest conditions, since the weakness of the pairs in the oven spectrum shows that an abnormal stimulus is required to give them the intensity which they have in arc and spark.

2. *Band spectrum.*—The set of bands in the green-yellow are given very strong by the oven. Their structure is worthy of more detailed study than I could make with the dispersion available, and, judging from visual observations of the bands of *Ca* and *Sr* in the

[1] H. Kayser, *Handbuch der Spectroscopie*, II, p. 671.

less refrangible part, these are very similar. Fig. 2, No. 3, shows these *Ba* bands, somewhat overexposed to bring out the weaker portions. While the bands evidently have their heads toward the violet, the successive members of the group show a shift of the maximum intensity in each band. The first band at the red end of the group has its intensity concentrated in the head, this being so strong as to be ill-defined. The second band has a sharply defined head with a considerable extension toward the red. In the third band the whole structure is resolved into fine lines of nearly equal intensity, the head being stronger and reversed. In the fourth band, the red end, which we may call the "tail," is much stronger than the head, which is still visible. The fifth shows the intensity more concentrated in the tail, with only a trace of the middle, while in the sixth only the tail is visible.

A second and new group of bands appears in the ultra-violet, very weak in comparison with the green series. I have measured eight bands here, some very faint, but two of them having fairly sharp edges toward the red. The bands are too weak to decide if a structure similar to that of the green bands is present here. The approximate wave-lengths follow:

3646	diffuse	3822	diffuse, fairly strong
3694	diffuse	3872	well-defined edge toward red
3725	diffuse	3922	well-defined edge toward red
3768	diffuse	3961	faint

COPPER

Metallic copper in the oven gave a combined line and band spectrum.

1. *Line spectrum.*—A comparison of the lines obtained in my oven with the behavior of the same lines in the arc and spark spectra previously studied[1] leads to some interesting conclusions. The lines given by the oven are few and are not the lines most prominent in the arc. I have obtained only λλ 5106, 5700, 5782, there being no trace whatever of the pair λλ 3274, 3247, which are always the strongest lines in the arc or spark spectrum, of the first sub-series pairs λλ 4023, 4063, 5153, 5218, always strong in the arc, and numerous other prominent lines. The action of λλ 3274, 3247 is significant as indicating that the chemical action in the oven is very weak. W. Lansrath,[2]

[1] A. S. King, *Astrophysical Journal*, **20**, 21–40, 1904. [2] *Dissertation*, Bonn, 1904.

who recently photographed the oxygen-coal-gas flame spectrum of *Cu* with the same grating and same sort of plates, records these lines as always appearing strongly in the flame, usually reversed. In my photograph, the comparison arc spectrum gives the lines in their usual strength, but the oven spectrum shows nothing beyond the cyanogen band λ 3590, though the temperature of the oven must be considerably higher than that of the flame. The conclusion to be drawn, then, is that the conditions other than high temperature which produce these lines in the flame are absent or very weak in the oven. The temperature of the oven is not high enough to give lines of so short wave-length in any spectrum studied, so we should not expect them to appear if the radiation of the oven is chiefly a temperature effect.

The strength of the green lines 5106, 5700, 5782, combined with the absence of the pair 5153, 5218, is approached in the arc only when the current is very weak, as 0.5 ampere, and still closer when with a current of 1 ampere the outside layer of luminous vapor was projected on the slit. In this latter case the weakness of the pair compared to λ 5106 was striking. As the current rose above 0.5 ampere, the pair increases in relative strength until at about 6 amperes its weaker member λ 5153 is equal to λ 5106, and with still higher currents surpasses it in strength. As was noted in the former paper, the arc with high voltage and only 0.3 ampere, given by a succession of flashes, resembles in many respects the arc with high current, unusual conditions apparently being given by the interruption. In the spark, λλ 5153, 5218 are always strong except under those conditions, such as the spark with self-induction or with hot electrodes, in which the relative intensities of lines approach in some degree those of the arc.

Thus the copper lines as given by the oven would seem to indicate conditions a grade lower than the weakest arc; while the total absence of the strong ultra-violet pair speaks for an absence or great weakness of luminous processes other than temperature.

2. *Band spectrum*.—The oven proved very efficient in producing the banded spectrum when metallic *Cu* was vaporized in the tube. The bands with heads at λ 4005 and λ 4280, both running toward the red, are given very distinctly, with a fine resolution of their compo-

nent lines. In the prismatic spectrum I obtained the band λ 4280 strongly reversed. These bands in the flame were photographed by Hartley and recently measured by Lansrath. Besides these, the bands at λ 4649 and λ 4689 appear, which have been observed in the flame; and in addition the oven gives three other bands evidently belonging to the group and of the same dense structure. These are stronger than the two bands already known, but are probably concealed by the continuous ground in the flame spectrum. I have measured the heads of these as λλ 4598, 4547, 4499. Like the other bands, their edges are toward the violet and are fairly sharp.

IRON

The impurities in the carbon tube gave a large number of iron lines, and the number was not greatly increased when iron was vaporized in the tube. This metal showed very well the differences between arc and oven spectra, many relative differences in intensities of lines appearing. In the best photograph obtained, with the spectrum of the iron arc beside that from the oven, several lines in the blue were of the same intensity in both. These were λλ 4482, 4461, 4427, 4376. Many arc lines as strong as these, and some stronger, did not appear at all with the oven, and others were relatively much weakened. In the following table some of the stronger lines are selected and their intensities compared, to give an idea of the sort of differences which appear in the two spectra:

λ	Arc	Oven	λ	Arc	Oven
3878.75	8	2	4308.09	10	2
86.45	6	2	25.97	10	2
95.83	4	1	76.11	2	2
99.89	4	1	83.71	15	3
3920.42	5	1	4404.95	12	2
23.10	5	1	15.31	10	½
28.10	6	1	27.50	3	3
30.49	6	1	61.83	2	2
69.41	8	0	82.39	2	2
4005.42	8	0	4528.80	6	0
45.99	12	1	5269.72	8	2
63.77	11	1	5328.21	6	3
71.92	10	1	71.67	6	3
4132.25	8	½	97.32	3	1
44.05	10	½	5429.81	3	1
4250.99	9	0	....	.	.
60.68	9	0	....	.	.
71.95	12	2	....	.	.

This table shows something of the differences which result from the conditions of the arc, as compared with the lower temperature of the oven combined with absence of electrical action.

MAGNESIUM

With either metallic *Mg* or the carbonate in the tube, a rather weak line spectrum appeared consisting of the triplets with strongest lines at λ 3838 and λ 5184 and the arc line λ 4571.31. The relative intensity of these lines is very different from that of the arc, and the strong arc lines λλ 4352, 4703 do not appear with the oven at all. The intensities of the lines in the two cases are approximately as follows:

λ	Arc	Oven
3829	15	12
3832	20	15
3838	40	30
4352	5	0
4571	2	50
4703	8	0
5167	8	8
5173	12	12
5184	20	20

From this it is seen that the violet triplet is weakened by the oven with respect to the green triplet, while λ 4571, one of the weakest arc lines, attains a quite abnormal intensity. My results for *Mg* permit of little comparison with those of Nasini and Anderlini[1] beyond the fact that my photographs do not show the lines which they consider to be those of nitrogen, given when the oxygen is used up by combination with *Mg*.

NEGATIVE RESULTS WITH MERCURY AND ZINC

These metals were used in large quantities in the oven at maximum temperature without any of their lines being obtained. It may be that their spectra require still higher temperature or electrical action, but it is quite possible that when such metals are vaporized in air they oxidize before the vapor is heated sufficiently to emit.

FURTHER OBSERVATIONS

Lead.—The strong arc line λ 4058 proved very sensitive, appearing almost always from impurities in the carbon. When metallic lead was vaporized in the tube this line appeared strongly and also the

[1] *Loc. cit.*

two lines λλ 3640, 3684, these last, as compared with λ 4058, being much weaker than in the arc.

Aluminium.—Impurities in the carbon always gave the pair λλ 3944, 3962, and when the metal was introduced these lines were very strong.

Sodium.—The D lines appeared under all conditions, being extremely sensitive and appearing long before the oven reached a temperature sufficient to produce other lines. Metallic *Na* could not be used in the oven to give a greater vapor density, as it appeared to act on the cementing material of the carbon, causing immediate disintegration.

Manganese.—The lines of the violet triplet λλ 4031, 4033, 4035 are noteworthy for their sensitiveness and easy reversibility. The triplet always appears strongly, given by impurities, and this small quantity of the vapor sufficed to give the lines reversed when a continuous ground was produced. In these properties this triplet ranks with the D lines and *g* of calcium.

Lines given by small impurities.—As an example of the usefulness of the oven in bringing out lines when only a minute quantity of the element is present, it may be of interest to note the elements represented in a photograph taken with cæsium sulphate in the tube, the sensitiveness of the plate extending only to about λ 4600. Here the lines other than *Cs* could come only from impurities in the salt or in the carbon.

Sr	4607.51
Cr	4289.92, 4275.01, 4254.52
Ca	4226.90
Rb	4215.75, 4202.00
Ga	4172.22
Pb	4058.00
K	4047.42, 4044.30
Mn	4034.62, 4033.21, 4030.92
Al	3961.71, 3944.20
Fe	28 lines identified

These, with the D lines of *Na*, the *Cs* lines and the cyanogen band 3883 give a total of thirteen elements represented in the spectrum given by a "chemically pure" salt in the tube.

Arc spectrum given by ionized vapor.—It was shown in the course of these experiments that vapor coming directly from the arc, espe-

cially when confined, gave the arc spectrum, though quite out of the path of the current. Several times when a hole was burned in the bottom of the carbon tube, the arc spectrum appeared at once from the vapor streaming up into the tube, though the arc itself was entirely below. Also when the tube was moved so that the arc struck close to its end instead of at the middle, the vapor rising past the end showed the arc spectrum of the carbon and impurities. The regular position of the arc striking the middle of the tube did not allow of any arc vapor coming into the region projected on the slit.

Effect of water vapor.—To see if the hydrogen lines would appear from water vapor in the oven, as they are known to come when water is dropped into the arc, a current of steam was passed into one end of the tube, the other being closed by a window at the end of the asbestos extension tube; while a small hole in the side of the carbon near its middle, inside the inclosing blocks, gave an outlet for the steam, leaving the tube almost air-tight. The hydrogen lines did not appear but other lines, evidently belonging to impurities in the carbon, were rendered very bright by the contact of the steam. These were in the green and red, about λ 5500 and λ 6200 respectively, and may have been calcium lines which have only a moderate strength in the arc; but as the observations were made visually with a small dispersion, they were not certainly identified. The steam caused the red line to become very brilliant and reverse, and a little farther in the red a very diffuse banded structure appeared with much steam in the tube, not distinct enough for identification. This strengthening of certain lines through the presence of water vapor may have interesting applications in the further study, though at present its process is obscure.

DISCUSSION OF RESULTS

The chief significance of the foregoing results is that they have been obtained by a method which, while giving a high temperature, excludes the electrical action always present in the arc or spark. The electrical action here meant is that which arises from the vapors carrying the electric current. The arc is used merely as a source of heat. The intense heat must produce a certain degree of ionization of the vapor inside the tube, and electrical action in this sense is present; but this would be true if the tube could be heated to the same degree by a gas flame or coal furnace.

Chemical action is undoubtedly present when the oven is used in air, and the complete exclusion of possible chemical action would seem to be impossible, since the vapor must always be heated in a closed space, and this even if evacuated would offer the possibility of chemical action between the vapors and the walls of the containing vessel, as combinations might be formed under such conditions which are unknown at ordinary temperatures.

Allowing then for the possibility of such action by other agents, my evidence in favor of temperature as the chief agent in giving the observed effects lies mainly along three lines:

First, in every case which was tried, the production of a strong continuous ground by the introduction of a small carbon rod in the oven tube was found either to quench or reverse all emission lines, showing that the radiation of a black body at the same temperature was always stronger than that of the luminous vapor—a condition which might or might not be true if these lines owed their radiation to sources other than temperature. Even the D lines followed this rule, though they appear at such comparatively low temperatures as to suggest a chemical luminescence. If the tube contained glowing solid matter, lines were seen reversed against the background thus given and bright in the free part of the tube.

Second, the spectrum given by the oven appears to have a limit at its violet end which is never overstepped, even when lines usually strong in the arc or spark should appear slightly beyond this limit. The temperature which I have been able to produce gave no lines in my photographs below λ 3500, though the plates were sensitive to the arc spectrum as low as λ 2200. The copper spectrum gave the best example of this action. As has been noted, no trace appears of $\lambda\lambda$ 3274, 3247 which in all arc and spark spectra in air are much the strongest lines of the spectrum, while lines are given by the oven which in the arc are much weaker than this pair. If conditions other than high temperature are necessary to produce these lines, such conditions are not strong enough in the oven to bring out lines beyond the limit apparently set by the temperature.

The third evidence may be drawn from the shift of the maximum in the cæsium series with higher temperature. Unless the chemical action in the tube is capable of changing the maximum of radiation

as the action becomes more vigorous (which, so far as I know, has not been observed in other experiments), the only alternative seems to be to recognize the temperature as the agency in shifting the maximum, and, if so, as the cause of radiation.

The foregoing observations have been obtained with the apparatus in its simplest form, the purpose being largely to develop the possibilities of the method. Numerous refinements are possible, not only in improving the efficiency of the oven, but in excluding possible chemical action. The work next in view along this line is the construction of the oven in a closed chamber which may be either evacuated or filled with pure gases.

SUMMARY

The chief results may be summarized as follows:

1. The oven produces emission spectra containing numerous lines whose relative intensities are very different from the lines of the arc spectrum.

2. The method is especially favorable for the production of banded spectra.

3. The changes in intensity of the cæsium series lines with the temperature indicate that an incandescent vapor follows the law of radiation of a solid body.

4. A comparison of series lines in arc and spark spectra of several elements points to an effect by altered electrical action similar to that of changed temperature.

5. The calcium spectrum from the oven shows: (*a*) great sensitiveness to slight changes of temperature; (*b*) a peculiar behavior of the H and K lines, which appear only at maximum temperature and then very weak; (*c*) *g* shows an unsymmetrical broadening of reversal, giving an apparent displacement; (*d*) using the vapor in the oven as absorbing medium showed the absorption of *g* to be much greater than that of other calcium lines and to vary with the temperature of the oven.

6. The pairs of homologous lines in the spectra of *Ca*, *Sr*, and *Ba*, belonging to the same magnetic type, are in each case much weakened in the oven spectrum as compared to the arc.

7. The oven spectrum shows new groups of bands in the spectra

of *Ca*, *Sr*, *Ba*, and *Cu*. The structure of the green band-group of *Ba* seems to result from a shift of maximum intensity through the successive bands of the group.

8. The relative intensities of copper lines given by the oven approach those of the very weak arc. The absence of the ultra-violet pair speaks for temperature as the chief agent in producing the spectrum.

9. In many cases a very small amount of a substance in the oven served to give characteristic lines.

10. It was shown incidentally that ionized vapor direct from the arc, when confined, would give the arc spectrum, though out of the path of the current.

11. Water vapor in the oven had the effect of intensifying certain metallic lines.

I wish to express to Professor Kayser my appreciation of the interest he has taken in the work and of the valuable advice he was always most ready to give.

PHYSICAL INSTITUTE, UNIVERSITY OF BONN,
October 1904.

THE TEMPERATURE OF THE SOLAR ATMOSPHERE

By ARTHUR SCHUSTER

Two years ago I published in this *Journal* an investigation on the "Absorption and Radiation of the Solar Atmosphere," which has recently been commented upon by Mr. Very. Scientific discussion is unprofitable if criticism is based on misunderstandings for which the criticised author is not responsible; and that this is the case in the present instance appears from the two following sentences, among others, quoted verbatim from Mr. Very's paper: "The symbol I is used for photospheric radiation, and F for the 'radiation of a perfectly black body which is at the temperature of the shell' constituting the absorbing atmospheric layer. This supposition implies that the absorbent matter consists of perfectly black particles suspended in the medium."

Everybody knows that the function of temperature and wave-length which expresses the radiation of a black body is a fundamental function which must enter into every discussion of radiation and absorption. Yet, for the reason that I have introduced the symbol F for this function, and for that reason alone, Mr. Very accuses me of having tacitly introduced an assumption into my equations which begs the question. There is, of course, no foundation for Mr. Very's conclusion. A glance at the equation which forms my starting-point would have shown him that I took the radiation of the layer in question to be proportional to kF, and as k may have any possible value between zero and infinity, and may also depend on the wave-length, every possible case of absorption is included in my equations.

Among the questions raised by Mr. Very the only one on which argument is possible is the location of the absorbing layer. I ought perhaps to have been a little more explicit on this point, but, as regards the main purpose of the investigation, it was a point of secondary importance only. It will be remembered that my object was to explain the apparent diminution of intensity of radiation observed near the Sun's limb. The obvious explanation that an

absorbing shell was the cause of the diminution apparently did not fit the facts, as it gave a law for the rate at which the radiation diminished which was not consistent with observation. I showed that observation and theory were easily reconciled by taking account of the *radiation* as well as of the absorption of the interposed shell. The amount of radiation necessary showed that the absorbing layer must have a temperature not very much less than that of the photosphere. I added that I saw no reason to look for a different region in the Sun's surroundings for the cause of the observed diminution of radiation than that which gives the Fraunhofer lines. I obviously did not here refer to the region of the chromosphere. Nor did I mean my words to apply to the region which appears at the beginning and end of eclipses and gives us what is called the flash spectrum, though there may here have been a reasonable ground for misunderstanding. All I meant to imply was that, because in the region in question absorption outweighed radiation as regards the continuous spectrum, it would also do so for the line spectra of metals, and that therefore this region must contribute to the Fraunhofer absorption lines.

As misunderstandings seem so easily to arise, it is perhaps worth pointing out that, although for the purpose of facilitating mathematical analysis it is sometimes necessary to treat the upper portion of the same body as made up of distinct layers, having different temperatures and possibly different absorbent properties, the result of the analysis would, at any rate, in the present problem be the same had I taken the variation of temperature to be gradual instead of sudden. Even for the purposes of ordinary discussion we speak of the photosphere and of the absorbing layer, without wishing to imply that there is an abrupt transition from one layer to the other. If anyone desires to include the region in which radiation just falls short of absorption under the name of the photospheric layer, I have no objections. As far as this portion of the argument is concerned, it is one of nomenclature only.

I should probably not have taken space for an answer to the objections which have been raised, with insufficient cause, though they have been indorsed by an abstractor in the *Beiblätter*, had I not wished to correct an error for which I cannot offer any excuse.

The layer which for shortness I call the absorbing layer has a temperature which can be calculated in two different ways, if the temperature of the photosphere is assumed to be known. We may use for the purpose either the wave-lengths at the maxima of radiation, or the relative values of the radiation at the maxima. The ratio of the wave-lengths at these maxima, which also, taken inversely, is the ratio of the temperatures, was correctly given in my paper as 0.84. But the temperature was erroneously stated to be as the fourth power of the maximum radiation, while it ought, of course, to have been put equal to the fifth power. This improves the agreement. The maximum of the photospheric radiation in terms of an arbitrary unit is somewhere between 1.7 and 1.75, and the maximum radiation of a black body at the temperature of the absorbing layer in terms of the same unit is shown by my curves to lie about 0.62. This gives for the calculated ratio of temperatures a value somewhere between 0.81 and 0.82, numbers indicating a remarkable coincidence with the ratio of 0.84 calculated by the first method. In the rough examples given in my paper I took 10,000° for the temperature of the photosphere. To be more exact, we ought to put about 6,000° for the combined radiation of the two layers. This would give about 6,700° for the photospheric layers and about 5,450° for the temperature of the absorbing layer. With the exception of the numerical error now corrected, the reconsideration of the whole problem leads me to reaffirm all previous conclusions, which may be more strictly formulated thus:

There is a stratum near the Sun's surface having an average temperature of approximately 5,500° C., to which about 0.3 of the Sun's radiation is due. The remaining portion of the radiation has an intensity equal to that due to a black body having a temperature of about 6,700° C.

This conclusion is based on the supposition that the effective temperature of the Sun is 6,000°, and that the law of diminution of the average intensity of radiation with increasing distances from the Sun's center is correctly represented by Mr. Wilson's numbers, as quoted in my previous communication.

THE UNIVERSITY,
Manchester, England,
December 1904.

THE WORK OF THE RUMFORD SPECTROHELIOGRAPH

By GEORGE E. HALE

A paper on the Rumford spectroheliograph, published by Mr. Ellerman and myself as Part I, Vol. III, of the "Publications of the Yerkes Observatory," has been reviewed by several writers, to whom we are indebted for the careful discussion they have given to the work of the instrument.[1] In the course of these reviews certain questions have been raised regarding our interpretation of phenomena shown in the photographs. It is my object in the present paper to reply to these questions, in order that the true purpose and function of the spectroheliograph may be made as clear as possible.

Taking the reviews in order of publication, we come first to the interesting and valuable article by Mr. Evershed in the April 1904 number of *The Observatory*. Since Mr. Evershed's own work with the spectroheliograph dates back to 1892, it is obvious that his criticisms deserve most careful consideration. In one particular Mr. Evershed's interpretation of the spectroheliograph results differ from the one which we have employed as a working hypothesis. He is inclined to adopt the view that photographs taken with the second slit set on H_1 or K_1 represent the true faculæ, rather than the low-lying, dense vapor of calcium. His remarks on this subject are as follows:

> In discussing the results obtained in this way, Professor Hale adopts this view as a "working hypothesis," namely, that the calcium flocculi are depicted sectionally in at least three different levels above the photosphere, and the evidence afforded by these photographs certainly seems to bear out this idea. A serious objection, however, would seem to follow from the fact that in the photographs

[1] J. Evershed, "The Rumford Spectroheliograph of the Yerkes Observatory," *The Observatory*, April 1904. W. J. S. Lockyer, "A New Epoch in Solar Physics," *Nature*, April 28, 1904. E. Walter Maunder, "The Solar Atmosphere at Different Levels," *Knowledge*, July 1904. H. Deslandres, "Sur la photographie des diverses couches superposées qui composent l'atmosphère solaire," *Comptes Rendus*, June 6, 1904. B. Hasselberg, "En ny spectroheliografisk metod," annual address before the Academy of Sciences, Stockholm, March 28, 1904. W. H. Julius, "Spectroheliographic Results Explained by Anomalous Dispersion," Royal Academy of Sciences, Amsterdam; Proceedings of the Meeting of June 25, 1904.

of the spectrum itself the true reversals of H and K seem to be entirely confined to the central H_2 and K_2 region of the lines. Only in the rare cases of violent eruptions are there ever any signs of lateral spreading of the bright lines; and the shading on each side appears almost always to be uniformly dark, except only where it is crossed by the faintly bright continuous bands of the true faculæ. These bands, however, sometimes give a deceptive appearance of true reversal of the shading, as is well seen in Plate II, Fig. 2.

An alternative hypothesis would be that the K_1 images really represent the true faculæ, and are photographed by the continuous spectrum superposed upon the K band. On this view they cannot be regarded as low-level *calcium* vapor. It is possible, however, that the true calcium emission may become evident where shown up upon the dark background of a spot. The interesting comparisons given on Plates V and VI would have been more instructive on this point had the region photographed been situated near to the limb, where the faculæ proper would have shown up in much greater contrast.

The increase in brightness of the flocculi with the slit set nearer the center of the band, but still outside K_2, might be explained as an effect of contrast only. It is to be borne in mind, however, that in this position, so near to K_2, there is the possibility of partial reflection of the bright K_2 from one of the (highly polished) jaws of the slit itself.

In favor of Mr. Evershed's view, we have the following arguments:

1. If, as Mr. Evershed believes, the dense calcium vapor which gives rise to the H_1 and K_1 bands lies "appreciably below and between the highest summits of the faculæ," we would naturally expect the spectroheliograph to show the true faculæ when the second slit is set on these bands; for the increased absorption due to the bands would cut down the brightness of the background, and leave the faculæ, assumed to be unaffected by this absorption, standing out in strong contrast. Moreover, on this assumption the contrast should increase as the second slit is moved nearer to the center of the bands, since the corresponding increase in the intensity of the dark bands would tend to reduce the brightness of the background upon which the faculæ appear in the photographs.

2. Mr. Evershed argues that if the H_1 and K_1 photographs really represent the low-lying calcium vapor, these dark bands in the solar spectrum should give indications of reversal where they cross the flocculi. As a matter of fact, such reversals do not seem to be present, at least in a great majority of cases.

Without regarding it as free from objection, I am still inclined to retain the working hypothesis employed in our former paper. The following considerations have led to this conclusion:

1. If Mr. Evershed is right in his view that the faculæ overlie the dense calcium vapor represented by H_1 and K_1, the continuous spectrum of the faculæ should cross these dark bands with no diminution of brightness. A clear understanding of the spectrum in this region can be obtained only from a study of photographs taken with very high dispersion. Plate XIV is a reproduction of such a photograph recently secured on Mount Wilson with a Littrow spectrograph of 18 feet focal length. The 4-inch plane grating, having 14,438 lines to the inch, which was formerly used with the Kenwood spectroheliograph, was employed in the present instance with an objective of 4 inches aperture and 18 feet focal length, serving for both collimator and camera. An image of the Sun was formed on the slit of the spectroscope by an objective of 6 inches aperture and $61\frac{1}{2}$ ft. (18.74 m) focal length, supplied with light by a 15-inch cœlostat.[1] The photograph reproduced in Plate XIV was taken in the third-order spectrum. The scale is sufficient to show that the continuous spectrum of the faculæ rapidly decreases in intensity as it approaches the center of H_1 and K_1, where it almost entirely disappears. All of the photographs I have examined show this effect with greater or less clearness.

It seems to me that under these circumstances we should hardly expect the photographs to show the *faculæ* with increasing contrast, as the slit is moved from the edge toward the center of H_1 or K_1. On the contrary, we should expect the contrast of the faculæ to decrease rapidly, whereas the phenomena we have attributed to low-level calcium vapor steadily increase in *contrast*, though their absolute intensity diminishes.

In the light of existing evidence, I regard the photosphere as composed of innumerable clouds of condensed vapor, forming the summits of columns extending radially outward from the Sun's interior. The distance from the Sun's center at which condensation occurs depends upon the temperature gradient and upon the nature of the vapors which compose the columns. Probably only a few easily condensable substances are represented in the photospheric clouds. At any rate, hydrogen, helium, and calcium rise above the point of condensation, and continue upward into the chromosphere and

[1] The entire apparatus was extemporized for use pending the erection of the Snow telescope on Mount Wilson.

prominences. Magnesium, sodium, iron, and other substances represented in the flash spectrum also rise above the photospheric level.

At certain parts of the disk, where the convection currents rising from the Sun's interior are especially strong, the level of condensation is carried farther from the center because of the higher temperature. These regions are the faculæ, which therefore resemble the other parts of the photosphere in structure, though the photospheric clouds which compose them attain higher elevations.

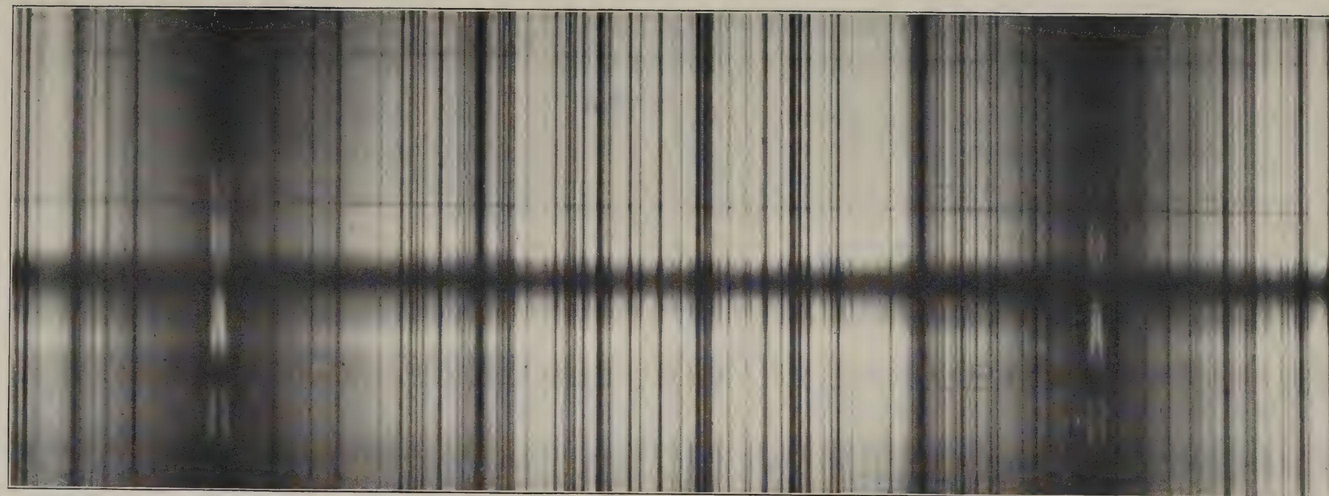
The height at which condensation occurs in the faculæ is ordinarily below the level attained by calcium vapor of such density as to produce bands of fully one-half the width of H_1 and K_1 in the solar spectrum. This is indicated by the fact that the continuous spectrum of the faculæ is usually weakened by absorption over more than half the width of these bands (Plate XIV). In general, the denser calcium vapor probably rises from the interior in the same columns with the vapors which condense to form the faculæ, though this does not always appear to be true. Hence, photographs of the faculæ, taken directly, or with a spectroheliograph having its second slit set on the continuous spectrum, will usually give forms resembling those obtained when the second slit is set near the edge of H_1 or K_1. The calcium vapor expands as it rises, and consequently the forms of sections of the flocculi, corresponding to higher levels, defined by the position of the second slit as it is set nearer the center of the band, will continue to show wider divergencies from the forms of the faculæ.

I believe that the evidence afforded by the flash spectrum as to the elevation attained by the denser calcium vapor will not be found to conflict with these views.

2. I frankly admit that I can offer no satisfactory reply to Mr. Evershed's second objection It certainly seems that H_1 and K_1 should show evidences of reversal over the flocculi, if they represent the calcium vapor in them. But one fact must not be overlooked: since calcium vapor undeniably extends deep into and below the photosphere, and since it has been shown to be so conspicuous in the H_2 and K_2 flocculi, it must play a very important part and

[1] This is clearly shown on the untouched photograph from which Plate XIV is made, though it may not come out well in the reproduction.

PLATE XIV



Decreased Intensity of Continuous Spectrum of the Faculæ on the H_1 and K_1 Bands

exhibit a wide range of density in the intermediate region. Hence, we should expect photographs taken with the second slit set on H_1 or K_1, close beside H_2 or K_2, to show bright areas intermediate in form between the faculæ and the H_2 or K_2 flocculi. This is precisely what we do get. These bright regions are greater in area than the faculæ, though they are inferior in this respect to the H_2 or K_2 flocculi. The area, as well as the contrast, of the flocculi increases as the second slit is moved toward the center of the band. Careful tests have been made to determine whether this increase in area (which is accompanied by changes in form) is to be attributed to an actual increase in the area of the flocculi. The results show, in my opinion, that the difference cannot be attributed to any effect resulting from increase of contrast arising from change of exposure time, or to other similar causes. Nor do I think the changes in form can be accounted for wholly by the effect of calcium vapor over the dark regions of sun-spots, where Mr. Evershed considers it might make its appearance felt. Reflection from the slit jaws, in such a way as to produce the phenomena observed, seems to me entirely out of the question.

If the objects photographed with H_1 or K_1 light were the faculæ, their forms should remain the same, whether the second slit be set on the continuous spectrum or at any point on the H_1 or K_1 bands (excepting, of course, at the center of the bands, where H_2 or K_2 light would enter). As we have already seen, however, neither the forms nor the areas remain constant.

Professor Schuster's very important paper on "Radiation through a Foggy Atmosphere"[1] has removed the difficulty of accounting for the bright H_2 and K_2 lines on the dark bands H_1 and K_1. In fact the bright reversals are precisely what we might expect, in view of the exceptional emissive power of these lines, and the great height to which calcium rises above the photosphere.

Dr. W. J. S. Lockyer, who reviews our paper in *Nature*, takes no exception to our working hypothesis on the photography of sections of flocculi corresponding to different levels. On the contrary, he gives a very lucid account of the method, illustrated by a diagram which brings out the principle involved in a very satisfactory manner.

[1] *Astrophysical Journal*, **21**, 1, January 1905.

Professor Hasselberg's address and Mr. Maunder's recent article in *Knowledge* also give a clear account of photography at different levels; but as they contain no criticism of our results, these papers require no reply.

Dr. Lockyer's difficulty relates to the question of bright and dark flocculi, especially with reference to the distribution of hydrogen and calcium vapor in the solar atmosphere. After referring to hydrogen and calcium in the flocculi, Dr. Lockyer remarks: "Since the *existence* of each of these substances on the Sun's disk is indicated by *bright* markings, it is not quite clear why Professor Hale calls the dark patches *dark calcium* or *dark hydrogen*, as in these parts calcium and hydrogen respectively are, according to the very principle of the spectroheliograph, shown to be *absent*."

In my understanding of the principle of the spectroheliograph, the instrument is quite as capable of recording defect of radiation as excess of radiation, i. e.; absorption phenomena are not less within its province than radiation phenomena. The spectroheliograph, according to this view, does not show that calcium or hydrogen are necessarily absent from any part of the solar disk. It simply indicates the existence of brighter or darker masses of these gases in certain regions. Thus, the dark flocculi shown on the disk, when the hydrogen line is employed, probably represent the higher and cooler masses of hydrogen gas seen in projection against the hotter and more uniformly diffused hydrogen in the lower chromosphere. Calcium vapor may also rise to a considerable height and cool to a temperature below that of the calcium vapor diffused throughout the lower chromosphere. Such a mass of vapor, if registered with a spectroheliograph of sufficient dispersion to permit photographs to be taken with the H_3 or K_3 line, would doubtless appear as a dark calcium flocculus. At present such objects are somewhat rare, since H_3 and K_3 are usually very narrow lines. Nevertheless, an illustration of a dark calcium flocculus, photographed with the spectroheliograph, is given in our paper.

I am therefore unable to agree with Dr. Lockyer's view, "that the regions where calcium exists correspond to those regions where hydrogen is absent." The known association of calcium and hydrogen in the chromosphere and prominences would seem to me to render such a

view very improbable, even if there were no other reasons against it. *Bright* hydrogen flocculi, in most cases easily distinguishable as such on the original negatives (but much less satisfactorily in the reproductions), are frequently found in disturbed regions, usually in the vicinity of sun-spots. *Dark* hydrogen flocculi, representing the absorption of comparatively cool hydrogen (probably, in most cases, at considerable altitudes) usually resemble, in general outline, the *bright* calcium flocculi in the same regions of the solar disk. As soon as it becomes possible to photograph with the H_3 or K_3 line, I think it probable that *dark* calcium flocculi, corresponding to the higher levels, will be frequently found in association with *dark* hydrogen flocculi. It will, of course, be understood that the term "flocculus," since it is used only to designate objects photographed in projection, does not, in itself, make any attempt to distinguish low-lying vapors from those immediately above them.

I am indebted to Dr. Lockyer for his article, and regret that I failed to make my meaning clear.

I wish I could conscientiously accept the compliment paid me by M. Deslandres, in ascribing to himself and to me the discovery of the flocculi in 1892. It is a well-known fact, however, that Professor Young, many years before, observed visually reversals of the H and K lines in the vicinity of sun-spots, and that Rowland and Jewell photographed these reversals before such investigations were undertaken by M. Deslandres and myself. I am sure that M. Deslandres will agree with me that the further records of this early work should also be accurately preserved, and that the photography of the *spectra* of flocculi should not be confused with the photography of their *forms* with the spectroheliograph. Since M. Deslandres has referred again to the history of the spectroheliograph, I may perhaps be pardoned for giving an outline of the facts. The spectroheliograph was first successfully employed in photographing the forms of flocculi at the Kenwood Observatory in the beginning of 1892, and Mr. Evershed constructed and used a spectroheliograph not many months later. In 1893 M. Deslandres obtained his first results with a spectroheliograph. In 1894, with a spectroheliograph having only a single prism, M. Deslandres made photographs of the solar disk with the second slit set on some of the dark lines. The images obtained in this way

are considered by M. Deslandres to represent the vapors in the reversing layer which correspond to the dark lines employed. He thus clearly recognized the principle which we have used in our more recent work; but his opinion as to the dispersion necessary in such work differs very widely from my own. Feeling certain that photographs obtained in this way, with an instrument of low dispersion, could not be depended upon to show anything more than the faculæ themselves (which can also be photographed by setting the second slit on the continuous spectrum), I did not think it worth while to make experiments in this direction until a suitable instrument should become available. The discovery of the dark hydrogen flocculi, and the results we have obtained with various lines of iron and other substances, are the natural consequence of employing dispersion sufficient to cause the dark line to cover completely the second slit. As I have always lacked confidence in experiments of my own with low dispersion, I have naturally felt that M. Deslandres stood equally in need of more powerful apparatus.

The paper of Professor Julius raises some questions of great interest, which I am not yet prepared to discuss in detail. While I think it possible that anomalous dispersion may ultimately prove to have a bearing on certain classes of solar phenomena, I have a strong belief in the objective existence of the photosphere, faculæ, spots, chromosphere, flocculi, prominences, and corona. On some other occasion I hope to have an opportunity to discuss the more general questions in the theory of Professor Julius. At present I confine myself to brief remarks on certain points raised in his discussion of the results obtained with the spectroheliograph.

The H_2 and K_2 lines are ascribed by Professor Julius, not to strongly radiating calcium vapor, but to light of nearly the same wave-length which has undergone anomalous dispersion in passing through a "tubular structure" containing calcium vapor. This explanation requires "that the brightness of the calcium flocculi must, as a rule, increase as the monochromatic light in which the Sun is photographed approaches the true absorption line." As a matter of fact, the *relative* brightness (contrast) of the flocculi increases as the slit is moved nearer H_2 or K_2, but their absolute brightness diminishes, so that longer exposures become necessary in successive

settings of the slit. In order that the contrast may increase, it is therefore necessary to suppose that the background decreases in brightness more rapidly than the flocculi.

The theory of anomalous dispersion requires, according toProfessor Julius, "the bright and dark structure generally to appear coarser and more woolly as the spectroheliograph is adjusted for kinds of rays that are more liable to anomalous dispersion"—i. e., as the second slit is moved toward the center of H_1 or K_1. As a matter of fact, however, it is mainly the larger flocculi that show such an effect, which we have attributed to expansion at higher altitudes. The finest and sharpest details ever recorded on our photographs were obtained with the H_2 line.

According to the theory of anomalous dispersion, the appearance of dark flocculi "is a direct consequence of the fact, that the particular distribution of the light in the solar image is not produced by local absorption and emission, but by irregular ray-curving. The rays are only caused to change their places; so an excess of light in the bright flocculi must necessarily be counterbalanced by a deficit in the surroundings." I do not think that a careful study of our original negatives would bear out this view, especially in the case of H_1 and K_1 photographs.

In my opinion, as already stated, the dark hydrogen flocculi are due to the absorption of comparatively cool hydrogen gas in the upper chromosphere and prominences. Professor Julius accounts for their darkness on the ground that "the ray-curving in the solar gases must generally be less with waves belonging to those narrower dispersion bands than with waves lying near the centers of the broad H and K bands." If "ray-curving" is a factor, and if the reasoning here is consistent with that in the first part of Professor Julius' paper, there remains the difficulty that the still narrower lines of iron and other substances give *bright* instead of dark structures.

Without further discussion, for the present, of Professor Julius' interesting paper, I can only say that our working hypothesis, though admittedly weak in some particulars, appears to me decidedly preferable to an explanation based wholly on the idea of anomalous dispersion. However, the possibility that anomalous dispersion may

in some degree affect results obtained with the spectroheliograph must not be overlooked in future work with this instrument.

While retaining our working hypothesis, I do so with full consciousness of its defects, and with a strong desire to remedy them, either by completing the present explanation, or by substituting a better general view, if such can be found.

MOUNT WILSON,
February 1905.

DISPERSION BANDS IN ABSORPTION SPECTRA[1]

By W. H. JULIUS

The appearance of absorption lines depends on various circumstances. As to the absorption phenomena in gases and vapors, such conditions as temperature, density, pressure, velocity in the line of sight, intensity and direction of magnetic field, have been fully studied and discussed. In the present paper we purpose to show that anomalous dispersion in the absorbing gas is also, to a great extent, accountable for certain typical features of the dark lines.

An originally parallel beam of light, when passing through a mass of matter the density of which is unequally distributed, will not remain parallel, and, generally speaking, the greatest incurvations will be noticed in those rays for which the medium has refractive indices differing most from unity; i. e., in those which, in the spectrum, lie closest to the absorption lines on either side. These particular kinds of light, while diverging into space, will spread in many more different directions than the average waves, and, as a rule, a smaller portion of them will fall into the spectroscope than of waves with refractive indices nearer to unity.

Accordingly, there must always be certain places in the absorption spectrum from which light is absent owing to dispersion in the absorbing vapor, for it may be taken for granted that the latter is never absolutely homogeneous. These darker parts in the spectrum we shall call *dispersion bands*. It stands to reason that these bands will overlap the regions of real absorption; so they might easily be mistaken for strengthened absorption lines, which no doubt has often been done.

We will now look somewhat more closely into the characteristics by which dispersion bands may be distinguished from absorption bands.

The curvature of a ray of light of a definite wave-length, at any point of a non-homogeneous medium, not only depends on the gradient

[1] A paper presented at the meeting on May 28, 1904, of the Royal Academy of Sciences of Amsterdam.

of optical density at that particular spot, but also on the angle which the beam makes with the levels of equal density. Its divergence will be the greatest when this angle is zero.

Strong ray-curving through anomalous dispersion in vapors may, therefore, be artificially produced in two ways: first, by using masses of absorbing vapor, presenting in a small space considerable differences in density, e. g., such as occur in the electric arc;[1] secondly, in larger spaces where the density varies but moderately, by making the light travel over a considerable distance under small angles with the levels of equal density.

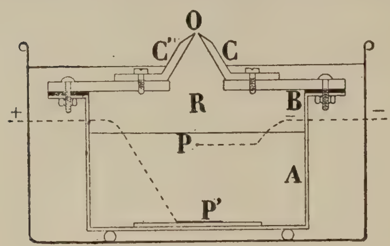


Fig. 1

I have chosen the latter method of investigation, especially on account of the extensive use which may be made of the phenomena presenting themselves, by applying them to the interpretation of numerous peculiarities of the spectra of celestial bodies.[2]

The absorbing medium was a Bunsen flame, of a peculiar shape, containing sodium vapor, and so arranged that the introduction of the salt could be easily regulated.

Fig. 1 represents a section of the burner. *A* is a copper trough, 80 cm long, 8 cm wide and 5 cm deep, thickly coated with varnish and having a broad flange. The planed brass plate *B* is firmly screwed upon the flange, and a leather packing makes the joint air-tight. On this cover, which has a rectangular opening 75 cm long and 2 cm wide, are fixed two brass rulers, *C* and *C′*, 75 cm long. They are so adjusted that at *O* they form a slit, having an exactly

[1] H. Ebert, "Wirkung der anomalen Dispersion von Metalldämpfen," Boltzmann *Festschrift*, p. 448.

[2] The abnormal solar spectrum of Hale; the peculiar distribution of light in several of the Fraunhofer lines, even in normal conditions; the variations in the average appearance of the spot spectrum accompanying the eleven-year period. All these phenomena have been easily explained from the considerations here alluded to (see W. H. Julius, *Astrophysical Journal*, **18**, 50–64, and *Proc. Roy. Acad. Amst.* **5**, 589–602; 662–666; **6**, 270–302).

The present investigation is a continuation of the experiments with the long sodium flame, a short account of which has already been given on those former occasions in support of our theory.

uniform width of about 0.1 cm over the whole length. The prismatic space between C and C' is closed at each end by a small triangular brass plate. The trough is filled to a certain height with a saturated solution of soda, and into the remaining space a mixture of illuminating gas and air is conveyed by means of tubes, entering at both ends. These tubes are fed from a mixing bottle in which the gas and the air are being driven through two separate regulating taps.

If now the flame were left to burn without any further precautions, the slit O would soon be closed in consequence of the one-sided heating of the rulers. It was therefore found necessary to place the trough in a vessel with running water, reaching up to the burner. In this way a uniform and steady flame was obtained.

A few millimeters below the level of the salt solution a platinum wire P is stretched over the whole length of the lamp. Its ends are soldered to insulated copper wires, which pass through the walls of the trough, and are connected to the negative pole of a storage battery of 20 volts. From the positive pole two insulated wires lead to the ends of a long strip of platinum P', which rests on a glass plate at the bottom of the trough. As soon as the circuit is closed, innumerable minute particles of the fluid rise into the space R, and cause the flame to emit a beautiful, clear, and constant sodium light, the intensity of which can be controlled and regulated by means of an ammeter and a variable resistance.

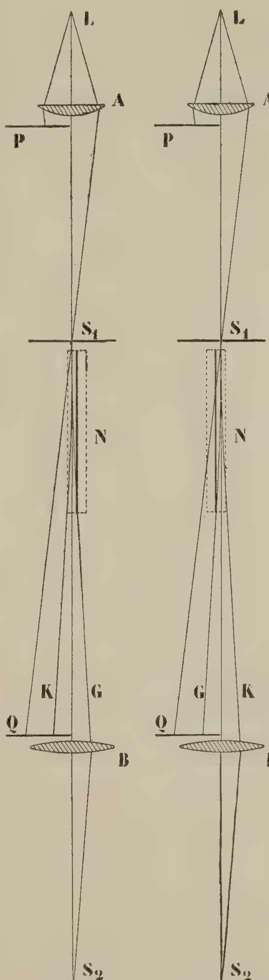


FIG. 2*a* FIG. 2*b*

In Fig. 2, *a* and *b*, are shown two different ways in which the light travels through this long sodium flame. L represents the crater of

an electric arc of 20 amperes. The lens A throws an image of the crater on the slit S, which, in its turn, is depicted by the lens B on the slit S of a grating spectroscope.

About half of the conical beam of light which leaves A is intercepted by the screen P, and the part which the slit S_1 allows to pass falls almost entirely on the screen Q, which has been shifted so close to the optical axis of both lenses that only a narrow streak of light can reach the slit S_2, through the middle of B. The large gas burner stands on a horizontal slide, which is movable up and down and around a vertical axis; thus, by means of screws, it can easily be put in any position required.

When the axis of the flame (which we assume to be in its most luminous part, i. e., a little above the blue-green core) coincides with the optical axis of the system of lenses, both the D lines will be seen symmetrically widened in the spectroscope. If not perfect, the symmetry will easily be corrected by slightly shifting the screens P and Q.

No. 1 of Fig. 3 (Plate XV) refers to the case when the flame N is not burning; the narrow absorption lines are due to traces of sodium surrounding the carbon points. When the flame is burning, a very weak current passing through the sodium solution will produce the effect shown in 2. The photographs 3, 4, and 5 were obtained with currents of about 1, 3, and 6 amperes, the flame always being in the symmetrical position.

We will now examine the case represented by Fig. 2, *a*. Here the axis of the flame has been shifted 3 mm toward the right. The narrow beam of light which reaches S_2 penetrates only that part of the flame where the density of the sodium vapor *increases* from left to right. In a structure of this kind waves for which the vapor has a great index of refraction deviate toward the right, e. g., S_1G. They are not intercepted by Q, and consequently reach the slit S_2. In fact, the presence of the sodium vapor allows similar waves to enter that slit even in larger quantity than they would do without it, for rays of this kind, issuing from the uncovered half of A, which if traveling in a straight line would be intercepted by Q, can, when refracted, penetrate the lens B.

The case is entirely different for those kind of rays for which

PLATE XV

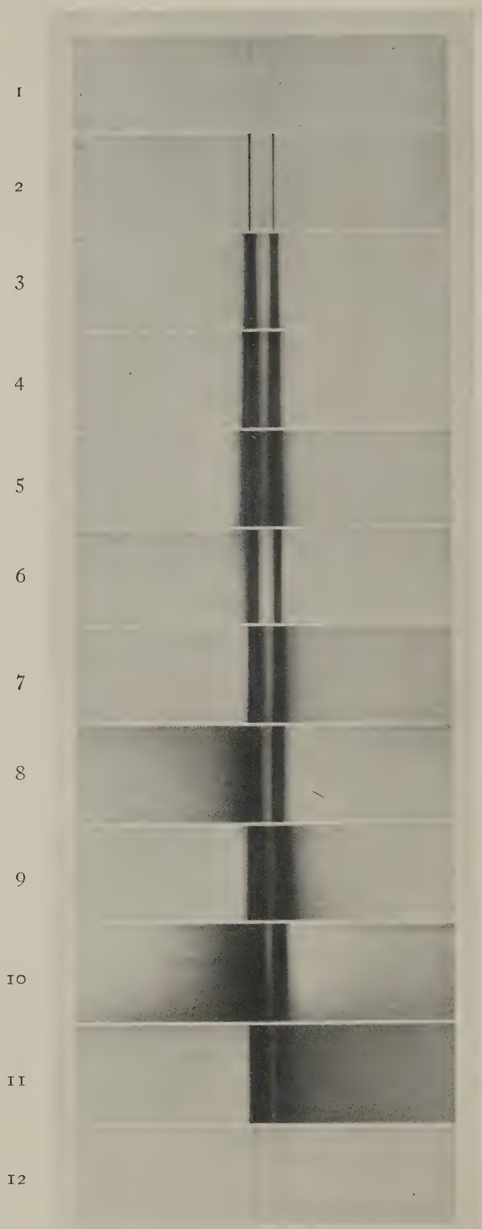


Fig. 3

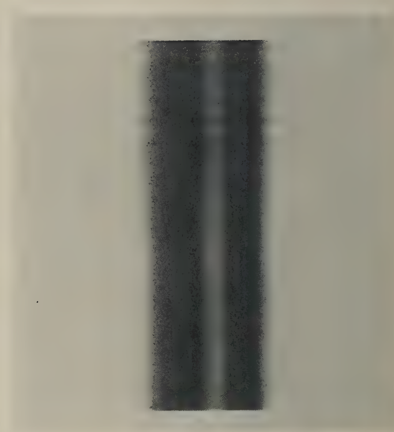


Fig. 4

Dispersion Bands in the Absorption Spectrum of Sodium

sodium vapor has refractive indices that are smaller than unity. Such rays deviating toward the left (as shown in S_1K) are intercepted by Q, and consequently will be absent from the spectrum.

Nos. 6, 8, and 10 are reproductions of photographs taken under these conditions. On the left are seen the smaller, on the right the greater, wave-lengths (in fact, in the whole series of photographs the stronger D line appears on the left side); so it is obvious that really the waves lying on the red-facing side of the D lines—i. e., those for which the vapor has high refractive indices—are *strengthened* by anomalous dispersion; and that, on the other hand, the waves on the violet side have been considerably *weakened.*

Alternately with 6, 8, and 10 the photographs 7, 9, and 11 were taken. The position of the flame was now as indicated in Fig. 2, *b*, i. e., its axis had been shifted 3 mm to the left, so that the central beam had to traverse that part of the flame where the density of the sodium vapor *decreases* from left to right. Here we notice that the rays with low refractive indices deviate toward the right and that a larger number of them reach the slit S_2, e. g., S_1K, while the rays with high refractive indices, such as S_1G, are intercepted by Q.

Nos. 6 to 11 show the effect of a gradual increase in the density of the sodium vapor. In No. 12 we again notice the sharply defined sodium lines after the flame has been extinguished at the end of the series of experiments; they are somewhat stronger than those at the beginning of the series, because much sodium vapor had spread through the room during the operations.

When carefully examining the original negatives it is possible in most of them to distinguish the rather sharp central absorption lines from the overlying dispersion bands (especially in the photographs obtained when the position of the flame was symmetrical; the reproductions fail to bring out this peculiarity). Advantage has been taken of this fact in so arranging the twelve photographs here reproduced that equal wave-lengths occupy corresponding places. Then it is seen that the "centers of gravity" of the two dark bands, as well as the brighter space between them, have been alternately shifted to the left and to the right—a phenomenon which needs no further explanation.

As a matter of course, the interposed flame causes the illumination in the plane of the slit S_2 to be very irregular, especially with regard

to those radiations undergoing anomalous dispersion in the vapor. It is evident that some kinds of rays which are absent from one part of that plane will be found in excess at another. The distribution of light in this irregular field of radiation might be explored by moving S_2, together with the spectroscope, within it. The same object can be obtained with less trouble by means of a thick piece of plate glass, mounted vertically between B and S_2 in such a manner that it may be moved around a vertical axis. When turning it a little we make the whole radiation field beyond the plate glass shift parallel to itself, thus causing other parts to cover the slit. This influences the aspect of the dispersion bands very materially. In certain positions apparent emission lines of sodium vapor may happen to be seen, which disappear as soon as the arc-light at S_1 is intercepted.[1]

In conclusion we wish to draw attention to a peculiarity we repeatedly observed in the dispersion bands. The dark shading in a dispersion band does *not* become deeper in proportion as we approach nearer to the central absorption line, but seems to reach its maximum obscurity at certain, though not always equal, distances on both sides of the center; while in the space between, the light appears somewhat intensified, just as if a wide absorption band had been partly covered by a narrower emission band, the center of which is again occupied by the fine absorption line. This phenomenon cannot, however, be attributed to radiation emitted by the absorbing sodium flame: for in our arrangement the intensity of the emission from the flame could bear no comparison with that of the arc for corresponding waves. In order to make sure, we tried to photograph the emission spectrum of the flame, exposing the plate during the same length of time and under the same conditions as had been done for obtaining the absorption spectrum; but not a trace of any impression could be detected on the photographic plate.

The light on both sides of the central line therefore originates in the carbon points, and this we explain on the principle of ray-curving. The kinds of rays which are most strongly refracted in the flame may, under certain conditions, be curved twice, or even more times, when passing nearly parallel to the system of the levels of

[1] These bright lines originate in the same manner as the light of the chromosphere. The chromospheric lines are not emission lines, but "bright dispersion bands."

equal density (in the manner described on a former occasion[1]), and will therefore have a greater chance of reaching the slit S_2 than rays which are less strongly curved. The relative intensity with which the waves belonging to those central parts of the dispersion bands appear in the spectrum increases with the distance over which the light has traveled along such a lamellar or tubular structure. Should the true absorption line happen to be exceedingly narrow, the dispersion band may give the impression of a double absorption band, which need not be symmetrical. In Fig. 4 on the plate is reproduced an enlargement of one of the photographs obtained by an almost symmetrical position of the flame.

We hold that the dispersion bands play an important part in many of the well-known spectral phenomena, such as the widening, shifting, reversal, and doubling of lines. In a subsequent communication I purpose to examine from this premise various phenomena observed in the spectra of variable stars and other celestial bodies.

[1] *Proc. Roy. Acad. Amst.* **5**, 596; *Astrophysical Journal*, **18**, 58, 1903.

SPECTROHELIOGRAPHIC RESULTS EXPLAINED BY ANOMALOUS DISPERSION

By W. H. JULIUS

It is not surprising that the scientific world should be highly interested in the beautiful results obtained by Hale and Ellerman with the spectroheliograph.[1] The brilliant method elaborated and applied by these investigators enables us to see at a glance, as well as to study in minute details, how the light of any selected wave-length was distributed on the total solar disk at any given moment. W. S. Lockyer, in giving an abstract from the paper here alluded to in *Nature*, No. 1800, rightly entitles it "a new epoch in solar physics." Indeed, the spectroheliograph proves capable of providing us with an abundance of new information, which other existing methods could never give, and the value of which will remain, whatever may be the ideas on the Sun's constitution derived from it.

But, nevertheless, even the most splendid collection of new facts is useless so long as we have no theoretical ideas connecting them with achieved knowledge. Hale and Ellerman, accordingly, in describing the observed phenomena, lay down quite definite conceptions regarding certain conditions and configurations of matter in the solar atmosphere, by which the observed distribution of the light in the image of the Sun is assumed to be produced. In the cited publication they put forth the working hypothesis that the "calcium flocculi," or bright regions showing themselves all over the image of the Sun when it is photographed in so-called calcium light, are columns of calcium vapor rising above the columns of condensed vapors of which the photospheric "grains" are the summits.[2] This hypothesis, though at first proposed mainly as a guide to further research,[3] has been subsequently[4] employed by the same authors with much

[1] G. E. Hale and F. Ellerman, "The Rumford Spectroheliograph of the Yerkes Observatory," *Publications of the Yerkes Observatory*, **3**, Part I, 1903.

[2] *Ibid.*, p. 15. [3] *Ibid.*, p. 13.

[4] G. E. Hale and F. Ellerman, "Calcium and Hydrogen Flocculi," *Astrophysical Journal*, **19**, 41–52, 1904.

less restriction as the basis on which the photographs ought to be interpreted.

The great authority of Hale and of such critics as W. S. Lockyer, J. Evershed, and others who, in abstracts from the work of Hale and Ellerman, concur in most of the interpretations there given, might cause the value of those ideas to become overestimated and extended beyond the original intention of the authors.

It is not superfluous, therefore, to show how we may quite as well account for all the new phenomena thus far revealed by the spectroheliograph, if we start from the entirely different conceptions of the Sun's constitution which the consequences of ray-curving in non-homogeneous media and of anomalous dispersion of light in absorbing vapors have suggested to us.

Both these circumstances are left absolutely out of consideration by Hale and Ellerman. Their conclusions are all founded on the erroneous supposition that the monochromatic light by which their images of the Sun are photographed has traveled from the source in straight lines, and that they are right, accordingly, in supposing light-emitting masses of calcium vapor to exist in the exact directions, along which calcium radiations seem to reach us. In making this supposition they fall into the same error as one who would assume the refracting facets of the crystal globe of a burning lamp to be independent sources of light.

Our new explanation of the spectroheliographic results will be founded on the hypothesis that the Sun is an unlimited mass of gas in which convection currents, surfaces of discontinuity, and vortices are continually forming under the influence of radiation and rotation, so that the various composing elements are mingled as completely as nitrogen and oxygen in the Earth's atmosphere.[1] This hypothesis too will, of course, want modification in the light of future results; but for the present it seems, so far as the visible phenomena are considered, not to clash with any observation or physical law.

The irregular motion of electrons in the deeper layers of the Sun, where the density is very great, gives rise to the radiation with a continuous spectrum. We shall take only *this* radiation into account.

[1] A sketch of a solar theory, based on this hypothesis, is to be found in the *Revue générale des Sciences*, **15**, 480–95, May 30, 1904.

Peculiar radiations, emitted by the more rarefied outer parts of the gaseous body and giving a bright-line spectrum, may perhaps add a perceptible quantity of light to the bulk, but this selective emission, if present, does not play any part in our explanations. So we behold the brilliant core of the Sun through an extensive envelope, consisting of a transparent but selectively absorbing mixture of gases, into which the core gradually spreads. It stands to reason that the average density of this envelope slowly decreases in the direction from Sun to Earth; but at right angles to that direction the density must be in some places much more variable. For it is a minimum in the axes of vortices; and the average direction of the whirl-cores, lying between the Earth and the central parts of the Sun in the surfaces of discontinuity, differs but little from our line of sight. The rays of the Sun thus reach us after having traveled a great distance along lines making small angles with the levels of slowest density variation in a lamellar, partly tubular, structure.[1]

Under these circumstances the solar rays will be sensibly incurvated on their way through the envelope, especially those suffering anomalous dispersion. As a rule, beams consisting of the latter kinds of rays will show an increased divergence; they will reach the Earth with less intensity than the normally refracted light, and so will give rise to dark *dispersion bands*[2] in the solar spectrum. And the degree of divergence will not only be different with waves which in the spectrum are found at different distances from the absorption lines, but it is also clear that the divergence with which various beams of *any definite* kind of light arrive at the Earth must differ largely according to the dioptrical properties exhibited along the paths of those beams by the system of surfaces of discontinuity.

The foregoing inferences really imply the whole of our interpretation of the results thus far obtained with the spectroheliograph. This we shall show by amply discussing some of their main features.

The broad dark bands, designated by Hale and Ellerman as H_1 and K_1, are not absorption bands, but dispersion bands. Real

[1] For considerations which have induced us to hold that a similar structure of the Sun is very probable, I refer to former publications: *Proceedings of the Royal Academy of Amsterdam*, **5**, 162–71, 589–602; **6**, 270–302.

[2] W. H. Julius, "Dispersion Bands in Absorption Spectra," *ibid.*, **7**, 134.

absorption by the solar calcium vapor we hold to be restricted to the central dark lines H_3 and K_3. The bright bands H_2 and K_2, predominating in the spectrum of the "flocculi," and attributed by Hale and Ellerman to strongly radiating calcium vapor, result in our theory from the fact that with beams of light the wave-length of which is very near to that of the central absorption lines, the divergence may be diminished, or even changed to convergence by the tubular structure. Indeed, such rays deviate more strongly than those standing farther from the absorption lines; and as soon as they undergo more than one incurvation, they have a chance of reaching the Earth with increased intensity. This chance improves in proportion as the index of refraction departs from unity, be it in a positive or in a negative sense.[1] We conclude from it that the brightness of the calcium flocculi must, as a rule, increase as the monochromatic light in which the Sun is photographed approaches the true absorption line.

This consequence of our theory exactly corresponds to one of the chief peculiarities, which immediately struck Hale and Ellerman on inspecting sets of photographs taken at short intervals of time with the second slit in different positions within the H and K bands. In order to account for the same fact, those investigators are obliged, by their working hypothesis, to suppose that in higher regions of the Sun's atmosphere the calcium vapor radiates more strongly than in lower levels. This cannot be called a very satisfactory inference, the less so since the supposition is added that the incandescent vapor is rising from much deeper layers and, therefore, considerably expanding—a process during which, according to our physical notions, the temperature must fall. Here we meet with a serious difficulty; Hale and Ellerman try to get rid of it by means of the rather vague assumption that some electrical or chemical effect may be responsible for the bright radiation emitted by this calcium layer, which is intermediate between two absorbing layers.[2]

Our theory can dispense with such additional hypotheses.

Another characteristic peculiarity, observed in every series of photo-

[1] In the experimental investigation on dispersion bands, before mentioned, this brightening in the middle of the dark bands has been distinctly observed. Cf. also *Proceedings of the Royal Academy of Amsterdam*, **5**, 596.

[2] *Astrophysical Journal*, **19**, 44, 1904.

graphs taken at short intervals with the slit set at various points on the broad H and K bands, is the following. When the slit is set, e. g., at a remote point of K_1, the structure of the solar image appears relatively fine, sharp, and detailed. Approaching the central line, we see some of the brilliant spots vanish. Others grow more extensive, especially those lying in the vicinity of sun-spots; at the same time their outlines become less sharp, so that finally the whole image gives us the impression of a coarser, and at the same time a more woolly, structure.[1]

Hale and Ellerman hold that the successive photographs refer to gradually higher levels, and conclude that the masses of calcium vapor must have a tree-like shape. W. S. Lockyer, in *Nature*, No. 1800, draws a scheme showing this conception.

Against this interpretation we propose the following one:

The amount by which the divergence of a beam of light is altered in consequence of the presence of calcium vapor in the streaming and whirling mass depends of course, on the proportion of calcium in the mixture, and, besides, on two other circumstances: (1) the position occupied in the spectrum by the selected kind of light with regard to the absorption lines, and (2) the steepness of the density-gradients in the mixture along directions perpendicular to the path of the beam.

Let us suppose the selected light to correspond to the extreme edge of H_1 or K_1, then its index of refraction differs but little from unity. Accordingly, very considerable inequalities of density are required to cause a perceptible change in the divergence of such beams. Similar great inequalities may indeed occur at many separate places, but at each of them they cannot, of course, extend very widely. This accounts for the fine and rather sharply defined reticulation shown by the so-called "low-level" photographs.

If the second slit were set a little nearer to the center of the line, the distribution of the light in the solar image would at all events differ considerably from that of the former case; for, the indices of refraction being very different for neighboring waves within a dispersion band, the divergence of beams, starting from the same point of the Sun, must vary largely with the wave-length. Thus it is clear that

[1] Such series of photographs are reproduced in *Publications of the Yerkes Observatory*, **3**, Part I, Plates V, VI, X, XI, XII, XIII.

bright or dark spots, visible on one photograph, may be wanting in the other.

Moreover, the general character of the image must change as we approach the central line; for in proportion as the indices of refraction depart from unity, slower variations of density suffice for producing sensible differences of divergence; and, as a matter of course, in any whirling region slightly inclined density-gradients will take up larger spaces than very steep ones. Besides, when the second slit of the spectroheliograph, having a given width, is set near to the central absorption line, the wave-complex which it allows to pass covers a greater variety of refractive indices than when it is set farther from the central line. In the former case the distribution of the light in the solar image must, therefore, be less differentiated. Both circumstances co-operate in causing the bright and dark structure generally to appear coarser and more woolly in proportion as the spectroheliograph is adjusted for kinds of rays that are more liable to anomalous dispersion.

From the same point of view it is not surprising that on photographs taken in H_2 or K_2 light the calcium flocculi are particularly bright and extensive in spot regions; for in such regions the "tubular" structure of the gaseous mass, by which the strongly curved rays are kept together and conducted, is most developed.

Hale and Ellerman also mention "dark calcium flocculi,"[1] which they describe as special objects, visible in so-called "high-level photographs," and not to be confounded with the general dark background produced by the absorbing vapor of deeper layers. Dark flocculi often surround the large bright flocculi of spot regions, as is shown, e. g., in Fig. 4, Plate V, of the cited publication. The explanation given by them is that we might have here some indications of the cooler K_3 calcium vapor, which rises to a considerably greater height than the K_2 vapor of the bright flocculi.

In our theory the presence of these darker regions is a direct consequence of the fact that the particular distribution of the light in the solar image is not produced by local absorption and emission, but by irregular ray-curving. The rays are only caused to change their places; so an excess of light in the bright flocculi must necessarily be counterbalanced by a deficit in the surroundings.

[1] *l. c.*, p. 19.

H and K are by far the broadest bands of the visible solar spectrum; even with moderate dispersion the second slit of the spectroheliograph could easily be set at different points within these bands. When the dispersion of the instrument was increased by means of a grating, photographs of the Sun could be obtained with light falling entirely within a widened line of hydrogen or of iron.

Photographs made with H_β or H_γ light showed also a flocky structure, differing, however, materially from that obtained with H and K. Hale and Ellerman therefore assume dark and bright clouds of hydrogen to exist in the solar atmosphere. Upon the whole, but not in the details, the hydrogen flocculi correspond in form and position to the calcium flocculi photographed with H_2 or K_2 light; the general aspect of the photographs is fainter, they show less contrast, and the detailed structure observed in H_1 or K_1 light is wanting. The most striking fact, however, is that *the bright calcium flocculi of the H_2 or K_2 photographs are replaced on the H_β photograph by dark structures of similar form.* Only in a few places in the vicinity of sun-spots small *bright* hydrogen flocculi occur which coincide with parts of bright calcium flocculi.

Hale and Ellerman hardly make an attempt to explain these facts which, in the light of their working hypothesis, are really puzzling.

We get a much clearer view of the matter as soon as we suppose the widening of the hydrogen lines also to be produced by anomalous dispersion, instead of by absorption only.

Indeed, the ray-curving in the solar gases must generally be less with waves belonging to those narrower dispersion bands than with waves lying near the centers of the broad H and K bands. Even in the powerful whirls of spot regions there will only sporadically be found places where the tubular structure is sufficiently marked to keep together rays belonging to the dispersion bands of hydrogen in the same way as it does gather the strongly curved H_2 and K_2 light in the large, bright calcium flocculi. Accordingly, we shall meet with very few places in bright calcium flocculi where the photographs in H_β or H_γ light also exhibit brilliant points. All the rest of the bright H_2 and K_2 regions correspond to those parts of the gaseous mass where the differences of density, though not so excessive, are nevertheless very considerable; but whereas in that structure the H_2 rays are

repeatedly curved and may be made to converge, the less strongly incurvated H_β rays will in the same regions diverge and be dissipated in a considerable degree, thus giving rise to dark places in the photographs. Outside the bright calcium flocculi, finally, where the H_2 and K_2 photographs are dark in consequence of increased divergence of the beams, no strong incurvation is given to the H_β or H_γ light. At those places the image of the Sun, photographed in hydrogen lines, must therefore be less dark.

The rather faint character of the hydrogen flocculi, and the absence of sharp outlines and of strong contrasts in the structural elements, we ascribe to the dispersion bands of hydrogen being relatively narrow and so allowing rays with a great variety of refractive indices to pass simultaneously through the second slit of the spectroheliograph. The hydrogen photographs, too, would show finer details, like those in K_1 light, if the dispersion of the apparatus were still greater and the second slit still narrower.

We believe that we have shown that every peculiarity thus far noticed in the photographs obtained with the spectroheliograph may easily be deduced from the same fundamental hypothesis regarding the constitution of the Sun which has already proved capable of giving a coherent interpretation of the solar phenomena known before. Not a single new hypothesis was required.

DISPERSION BANDS IN THE SPECTRA OF δ *ORIONIS* AND *NOVA PERSEI*[1]

By W. H. Julius

When light, giving a continuous spectrum, passes through a selectively absorbing, non-homogeneous mass of gas, the spectrum of the transmitted light contains places which, according to circumstances, may contrast as bright or as dark regions with their surroundings.[2] Though resembling emission and absorption lines, these bands have a wholly different origin. They are due to anomalous dispersion and, therefore, the name *dispersion bands* has been suggested for them.[3]

Dispersion bands always appear in the proximity of absorption lines, covering them more or less symmetrically; they show great variety in width and strength, and the distribution of the light in them may be irregular, so as to give the impression that one is witnessing cases of shifting or doubling or complicated reversal phenomena of widened absorption lines. All these cases can be produced almost at pleasure in the absorption spectrum of sodium vapor by merely varying the structure of the non-homogeneous medium through which the light is made to travel.

In the spectrum of the various parts of the solar image dispersion bands play an important part.[4] We can scarcely doubt that they are also present in stellar spectra; for the light coming from the stars must, as a rule, have traveled through immense gaseous envelopes and suffered ray-curving and anomalous dispersion, just as well as the light from the Sun.

Taking for granted that most of the visible stars are *rotating* gaseous bodies, with or without a solid core, we must suppose them to have a structure, describable by surfaces of discontinuity with

[1] A paper presented at the meeting on October 29, 1904, of the Royal Academy of Sciences of Amsterdam.

[2] *Proc. Roy. Acad. Amsterdam*, **2**, 580, 1900; *Astrophysical Journal*, **12**, 191, 1900.

[3] *Proc. Roy. Acad. Amsterdam*, **7**, 134–140, 1904.

[4] *Ibid.*, 140–147, 1904.

waves and vortices, and resembling the peculiar structure of the Sun, by which it has proved possible to explain solar phenomena.[1] Consequently, the stars too give existence to "irregular fields of radiation" rotating with them. Our line of sight continually cuts other parts of the refracting mass; it may pass closely along surfaces of discontinuity, now on the one, now on the other side of them; so the light reaching us must vary in strength and in composition.

The variability of many stars is very likely to result from this cause; and from the same principle it necessarily follows that their spectral lines should be liable to every kind of change in place and in appearance.

In many cases where the application of Doppler's principle leads to very unsatisfactory conclusions, the dispersion bands afford a plain solution. Let us consider, for instance, the spectrum of δ *Orionis*.

In this spectrum rapid changes in the position of the lines had been observed by Deslandres (1900), who concluded from them that δ *Orionis* was a spectroscopic binary having a revolving period of 1.92 days. Some observations made by J. Hartmann[2] did not agree with this period. Professor Hartmann therefore submitted the star to an extensive spectrographic investigation in the winter months of 1901–2 and 1902–3, and, from the forty-two plates obtained, drew the following conclusions:

The spectrum contains chiefly the lines of hydrogen and helium; besides a few belonging to silicium, magnesium, calcium.

The calcium line at λ 3934 (corresponding to K of the solar spectrum) is extraordinarily weak, but almost perfectly sharp; all the other lines (nineteen in number) are very diffuse and dim, often appear crooked and unsymmetrical, sometimes indeed double. While every prepossession of the observer was most strictly avoided during the measurements, it was found that the centers of the diffuse lines really oscillate, the period being 5.7333 days; but, owing to the unsymmetrical appearance of many of the lines, no evidence could be obtained that the values of the displacements were in mutual

[1] *Ibid.*, **5**, 162–171, 589–602; **6**, 270–302, 1903.

[2] "Unterschungen über das Spectrum und die Bahn von δ *Orionis*," *Sitzungsber. der K. Preuss. Akad. d. Wissenschaften*, **14**, 527–542, March 1904.

agreement for all the lines on one and the same plate. From the average displacements Hartmann calculated the "variable velocity in the line of sight," and finally the elements of the orbit.

An utterly surprising result, yielded by the measurements, was *that the calcium line at λ 3934 does not share in the periodic displacements of the other lines*, but shows a constant shift corresponding to a velocity in the line of sight of +16 km (reduced to the Sun).

Hartmann rejects the idea that this line should have originated in the Earth's atmosphere; also the assumption that it belongs to the second component of the binary system. He is thus led to the hypothesis that at some point in space in the line of sight between the Sun and δ *Orionis* there is a cloud of calcium vapor which recedes with a velocity of 16 km. By examining the spectra of neighboring stars no further information as to the existence of such a cloud was obtained.

A quite similar phenomenon, however, had been exhibited by the spectrum of *Nova Persei* in 1901: the lines of hydrogen and other elements were enormously broadened and displaced and continually changing their appearance, but during all the time the two calcium lines at λ 3934 and λ 3969, as well as the D lines, were observed as perfectly sharp absorption lines, yielding the constant velocity of +7 km. Hartmann therefore assumes that also in the line of sight between the Sun and *Nova Persei* there exists a nebulous mass consisting, in this case, of calcium and sodium vapor, and moving from the Sun at the rate of 7 km per second.

It must be admitted that these hypothetical clouds do not form a satisfactory solution of the problem.

A much simpler explanation of the phenomena may be derived from our conception of the irregular fields of radiation caused by the stars.

We need only suppose that the outer parts of δ *Orionis* and of *Nova Persei*, like those of so many other stars, contain much hydrogen and helium, little calcium and sodium. The currents and vortices in the gaseous mass, which produce the irregularities of the field of the star's radiation, bring about very broad dispersion bands in the vicinity of the lines of hydrogen, helium, etc. The darkest parts of these bands will be displaced when, by the star's rotation,

masses in which the density is variously distributed, pass our line of sight. The dispersion bands of calcium and sodium, on the other hand, are so narrow that the varying position of their darkest parts cannot be distinguished from the fixed position of the corresponding absorption lines. The constant displacement of the latter indicates that δ *Orionis* recedes from the Sun with a velocity of 16 km, *Nova Persei* of 7 km a second.

According to our opinion δ *Orionis*, therefore, is *not* a spectroscopic binary.

In the spectra of a great many stars oscillations and duplications have been observed only with diffuse lines. In those cases too the displacements are, as usual, expressed in so many kilometers a second, because no other interpretation than motion in the line of sight is thought of. From the above considerations it follows, however, that the observed oscillations are very likely to be executed by dispersion bands and not by the absorption lines; then no sufficient ground remains for classing such stars among spectroscopic binaries and for calculating orbital elements.

Several difficulties to which the conclusions derived from Doppler's principle lead us, will then disappear at the same time. How, for instance, are we to realize the physical conditions of the orbital motion in such so-called binaries as ι *Orionis*, 57 *Cygni*, θ^1 *Orionis* and many others, all of which are involved in nebulous matter, but whose motion in the line of sight is nevertheless—according to Frost and Adams — subject to periodical variations of 70, 90, 60 km a second, in spite of our physical notions concerning resistant media? When, on the other hand, the observed displacements of spectral lines, as well as the oscillations of the brightness of similar stars, are supposed not to result from motion in orbits, but from irregularities in their fields of radiation, there remains nothing astonishing in the fact that such variations often occur with stars involved in nebulosity.

In order to explain certain peculiarities in the spectra of *Novae* the principle of anomalous dispersion has already been applied by H. Ebert.[1] A characteristic of those spectra—viz., the presence of

[1] "Ueber die Spektren der neuen Sterne," *Astronomische Nachrichten*, **164**, 65, 1903.

double lines consisting of a bright and a dark component, the bright one being displaced toward the red, the dark one toward the violet—is very suggestively explained by this author in connection with the theory of Seeliger. According to this theory, the appearance of a *Nova* results from a dark or faintly luminous celestial body entering at a great velocity into a cosmic nebula. During this process the front part of the star's surface will become excessively heated and luminous, and a dense gaseous atmosphere will be formed, in which as Ebert shows, the incurvation of the rays must necessarily be such as to cause the dispersion bands appearing in the spectrum to be *bright* on the red-facing and *dark* on the violet-facing side of the absorption lines.

Ebert expresses the opinion that displacements and duplications of lines in the spectra of many variables of short period might be explained in a similar way, i. e., by admitting that the radiating power of such bodies is very unequal in different parts of their surface, and that they are surrounded by dense atmospheres. Their rotation will then cause us to see, as it were, the phenomena of the *Novae* periodically repeated.

In certain cases this interpretation may undoubtedly account for the peculiarities observed in the spectra of variables; nevertheless we cannot generalize the idea without meeting with some serious difficulties. First, it is not easy to form a clear conception of the physical conditions prevailing in a star, the incandescent surface of which is supposed to contain permanently large regions radiating very much less than the rest. The Sun with its spots may certainly not be adduced as an analogous case. Moreover, there are plenty of instances that in the spectrum of a variable, bright bands appear at the *violet* side, dark bands at the *red* side of the absorption lines, i. e., just the reverse of the phenomenon presented by the *Novae;* and it happens that with one and the same star bright and dark dispersion bands change places in course of time with respect to the average position of the absorption lines. This occurs, e. g., in the spectrum of *Mira Ceti*, as will appear when comparing the observations made by Vogel and Wilsing in 1896[1] with those made by Campbell in 1898[2] and by Stebbins in 1903;[3] also in the spectrum

[1] *Sitzungsber. der Berl. Akad.*, **17**. [2] *Astrophysical Journal*, **9**, 31. [3] *Ibid.*, **18**, 341.

of θ^1 *Orionis* observed by Huggins in 1894 and 1897,[1] etc. In those cases the explanation suggested by Ebert would require the addition of special hypotheses.

Our fundamental hypothesis, that the structure of most stars is similar to that of the Sun (it being admitted, of course, that the stars may greatly differ as to the extent of their respective gaseous envelopes, the average steepness of the density-gradients in them, their chemical composition, temperature, etc.), seems to admit of the interpretation of a greater variety of facts. It makes displacements of the dispersion bands toward the long and the short waves almost equally probable—if we leave the asymmetry in the form of the dispersion curves out of question and provisionally assume the directions of the axes of the stars to be distributed at random through space.

The direction in which we see a star may be regarded as a steady line in space, allowance being made for aberration and parallax. If, now, the distribution of the matter constituting that celestial body remains nearly unchanged for a long time, then after each rotation of the star our line of sight will again pass through the same points of the "optical system," and we shall observe an accurately periodical course in the star's brightness and in the appearance of its spectral lines. In most cases, however, currents and vortices will cause more or less considerable alterations to arise in the distribution of the density of the gaseous mass, and, consequently, in the composition of the beam of light reaching the Earth at a given phase of the star's rotary motion. Thus the strictly periodical succession of phenomena is open to any degree of disturbance. The very irregular and sometimes rapid changes in the brightness of objects like *o Ceti*, *SS Cygni*, μ *Cephei*, etc., are much more intelligible from this point of view, than from interpretations based on the assumption of violent eruptions, large spots, or eclipses caused by dark companions. And it is so difficult to make a sharp distinction between variables of long period and *Novae* that we should not resent the idea of comparing even the appearance of a new star to the sudden gleam of a revolving coast-light when the optical system, giving to the beam a considerable decrease in divergence, passes our line of sight.

[1] *An Atlas of Representative Stellar Spectra*, p. 140.

Minor Contributions and Notes.

STARS HAVING PECULIAR SPECTRA[1]

An examination of the photographs of the Henry Draper Memorial has led to the discovery, by Mrs. Fleming, of a number of variable stars and objects having peculiar spectra, in addition to those previously published. A list of these has been compiled by Mrs. Fleming, and is given below, together with a number of variables already known, for which the spectrum

PECULIAR SPECTRA

Constellation	*B. D.* No.	R. A. 1900	Dec. 1900	Magn.	Spectrum	Description
		h m	° ′			
Andromeda....	....	0 10.8	+46 27	...	Md	Variable. *X Andromedae*
Andromeda....	+38°315	1 33.7	+38 50	...	Md	Variable. *Y Andromedae*
Taurus.......	....	4 32.8	+ 8 9	...	Md	Variable
Orion........	+ 7°768	4 53.6	+ 7 59	...	Md ?	Variable. *R Orionis*
Orion........	+ 4°949	5 25.1	+ 4 7	...	K 5 M	Variable. Peculiar
Camelopardalus...	....	5 49.4	+74 30	...	Md	Variable. *V Camelopardali*
Monoceros....	−11°1460	6 16.8	−11 44	5.9	B Pec.	*Hβ* bright
Monoceros ...	− 2°1581	6 17.7	− 2 9	...	Md	Variable. *V Monocerotis*
Ursa Major...	....	8 33.9	+50 29	...	Md	Variable. *— Ursae Majoris*
Ursa Major...	+50°1603	8 56.2	+50 29	9.2	N	Peculiar
Virgo........	− 5°3456	12 9.5	− 5 29	...	Md	Variable. *T Virginis*
Boötes.......	+14°2700	14 1.7	+13 58	...	Md ?	Variable. *Z Boötis*
Libra........	− 2°3939	14 58.8	− 2 28	9.6	N	Peculiar
Norma.......	−54°6651	15 36.4	−54 40	...	Md	Variable. *T Normae*
Lyra.........	+36°3066	18 11.5	+36 38	...	Md	Variable. *W Lyrae*
Hercules.....	....	18 16.7	+31 41	...	Md	Variable
Sagittarius....	....	18 29.5	−31 47	...	Pec.	Dark bands
Lyra.........	....	18 42.2	+43 32	...	Md	Variable. *RW Lyrae*
Sagittarius....	−29°15574	18 52.4	−29 38	8.9	Pec.	Dark bands
Sagittarius....	....	19 8.5	−19 0	...	......	Variable
Sagittarius....	−33°14076	19 10.0	−33 42	...	Pec. !!	Variable. *RV Sagittarii*
Sagittarius....	....	19 13.8	−21 7	...	Md	Variable. *Z Sagittarii*
Cygnus.......	+49°3225	20 9.8	+49 9	...	Mc 5 d	Variable
Cygnus.......	+29°4231	20 50.9	+30 2	...	Md	Variable. *UX Cygni*
Cygnus.......	+39°4368	20 51.6	+39 55	7.2	Cont.	
Cepheus......	+64°1527	21 17.3	+64 27	5.5	B Pec.	*Hβ* bright
Pegasus.......	+24°4462	21 40.0	+24 33	...	Md	Variable. *RR Pegasi*
Cepheus......	+61°2246	22 2.1	+61 48	6.0	Pec.	
Cepheus......	+58°2402	22 8.1	+58 56	5.6	Pec.	*λ Cephei*
Cetus.........	−15°6531	23 57.0	−15 14	...	Md	Variable. *W Ceti*
Cassiopeia....	+54°3103	23 58.3	+54 60	7.9	Pec.	*Hβ* bright

[1] *Harvard College Observatory Circular* No. 92.

has recently been determined, and two additional objects found by other observers, as stated in the remarks following the table. The constellation and catalogue designation are given in the first two columns. The approximate right ascension and declination for 1900, and the catalogue magnitude except in the case of variables, are given in the third, fourth, and fifth columns. The class of spectrum and a brief description of the object are given in the sixth and seventh columns. The designations for stars north of declination $-23°$ are taken from the *Bonn Durchmusterung*, for stars between declinations $-23°$ and $-52°$ the *Cordoba Durchmusterung* is used, and for stars south of declination $-52°$ the *Cape Photographic Durchmusterung* is used. Each of the new variables has been confirmed independently by a second observer. Additional information regarding several of these objects will be found in the remarks following the table.

REMARKS

h m

4 32.8. This star varies probably more than three magnitudes, being as bright as the magnitude 9.0 on one of the plates examined, and fainter than 12 on two plates.

5 25.1. The spectrum of this star is between Classes K and M, and shows a bright line of slightly shorter wave-length than $H\delta$. The plates examined show a variation of about 0.7 magnitude, and, as in the case of the other stars, the variation has been confirmed by a second observer.

6 16.8. On a plate taken on October 16, 1904, with the 11-inch Draper telescope, the hydrogen line $H\beta$ is bright, $H\gamma$ is very faint and double, and the remaining lines of hydrogen and those of helium appear to be double. This is probably a spectroscopic binary. The spectrum of $-11°1478$, which is also on this plate, shows well defined single lines.

8 56.2. This spectrum extends beyond $H\epsilon$, having, besides the usual dark band in fourth type spectra, a second strong band near wave-length $H\delta$, and a third, between $H\delta$ and $H\epsilon$.

14 58.8. This spectrum shows the same peculiarities as that of the star, R.A. $8^h 56^m.2$.

18 29.5. This spectrum has a broad dark band which extends from about λ 465 to 471, and is of the same type as *C.DM.* $-47°6614$, described in Circular No. 76.

18 52.4. This spectrum is already known as peculiar, but is inserted in the table in order to describe it as belonging to the same type as *C.DM.* $-47°6614$, described in Circular No. 76.

19 8.5. This star was the comparison star "o" in the sequence selected for *RW* and *RX Sagittarii*, and during the observations of these stars the variation in this star was discovered by Miss S. E. Breslin.

20 9.8. An examination of 16 chart plates shows a variation of about a magnitude in this star.

20 51.6. On a plate taken on September 15, 1904, the spectrum of this star is continuous, and fails to show any trace of lines, although the lines in other spectra are well defined. On some of the other plates the hydrogen lines show faintly, even with the spectrum not so well defined.

21 17.3. On a plate taken on October 16, 1904, with the 11-inch Draper telescope' the hydrogen line $H\beta$ is bright, the other lines are broad, and the spectrum has the same general appearance as that of the star, R.A. 6^h $16^m.8$, although the lines in this spectrum do not appear double.

22 8.1. λ *Cephei*. The star ζ *Puppis* has a spectrum that heretofore has been regarded as unique. It contains, besides the usual series of hydrogen lines, a second rhythmical series also probably due to hydrogen, and only a few other lines. The southern declination of this star has rendered it difficult to study its spectrum at the great observatories in Europe, or in the United States. The spectrum of the northern star, λ *Cephei*, was found by the writer to be identical with that of ζ *Puppis*.

23 58.3. The hydrogen line $H\beta$ is bright and superposed upon a broad dark line. The lines $H\gamma$, $H\delta$, and $H\epsilon$ are narrow, and two other narrow lines having the approximate wave-lengths 416 and 420 are also present.

The variability of *C.P.D.*$-73^\circ.1134$, R.A.$=13^h$ $13^m.5$, Dec.$=-73^\circ$ $55'$ (1900), suspected by Kapteyn, has been discovered independently by Miss L. D. Wells, and shows a range of about a magnitude and a half.

EDWARD C. PICKERING.

DECEMBER 21, 1904.

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In the department of *Minor Contributions and Notes* subjects may be discussed which belong to other closely related fields of investigation.

Articles written in any language will be accepted for publication, but unless a wish to the contrary is expressed by the author, they will be translated into English. Tables of wave-lengths will be printed with the short wave-lengths at the top, and maps of spectra with the red end on the right, unless the author requests that the reverse procedure be followed.

Authors are particularly requested to employ uniformly the metric units of length and mass; the English equivalents may be added if desired.

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THE

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OBSERVATIONS OF THE RADIAL VELOCITIES OF THIRTY-ONE STARS MADE AT THE EMERSON McMILLIN OBSERVATORY

By H. C. LORD

For the past ten years observations of stellar motions in the line of sight have been made at the Emerson McMillin Observatory. Though not all the stars whose velocities it is possible to measure with this instrument have been observed, yet, in view of the optical giants at work in this branch of research today, and in further consideration of the fact that our sky is far from favorable for such work and that it is yearly getting worse, it seems advisable to draw the work to a close and turn to some other line of investigation better suited to our conditions. It seems proper at this time to publish the results thus far secured which have not as yet been given to the public, and to supplement them with a full description of the methods employed.

The instrument used is fully described in this *Journal*.[1] Certain changes have since been made, a description of which may be of general interest. In 1898 the results of a number of observations on

[1] *Astrophysical Journal*, 4, 50, 1896.

five stars were published. Those plates were all measured by the old Potsdam method of placing the star negative in contact, film to film, with a negative of the solar spectrum and measuring through the glass. Hydrogen alone was used as a source for the comparison spectrum. Shortly after these results were published, Campbell's classic paper, "The Mills Spectrograph of the Lick Observatory,"[1] appeared. Thereafter iron as well as hydrogen was always used as a source for the comparison spectrum. The method of reducing the plates is quite different from Campbell's, and an account of it will be given later.

The spectrograph as originally constructed was provided with two very dense flint prisms. These were so dense that the polished faces rapidly rusted and the spectrograms were fearfully unbalanced, being always underexposed on one side of $H\gamma$, and overexposed on the other. I was convinced that this defect could be largely reduced by the use of lighter glass. In order, however, to secure equal dispersion, it would be necessary to replace the two dense flints by three light ones; and it was a nice question as to how much the gain by the increased transparency of the glass would be counterbalanced by the increased loss by reflection. This can be easily predetermined, provided only we know the coefficient of absorption of the glass for the region of the spectrum covered. Such data are almost entirely wanting, so that it was necessary to measure this coefficient, not only for samples of glass kindly furnished me by Mr. Brashear, but also for the prisms of the old battery of dense flints. The observatory has a single dense-flint prism which, I believe, though I am not certain, was cut from the same block as the prisms of the battery. After many failures, I succeeded in giving the top and bottom faces of this prism a very fair degree of polish.

As this observatory has no apparatus for measurements of this kind, I was compelled to design and build one. The instrument finally used consisted of a spectrometer, the objective of whose collimator had been sawed in two like the objective of a heliometer, the two halves being separated. The slit was provided with a double set of jaws at right angles to one another; one, placed parallel to the refracting edge of the prism; the other, placed immediately in

[1] *Ibid.*, **8**, 123, 1898.

front of the first, serving to fix the width of the spectrum to a nicety. Upon looking into such an instrument, two spectra, illuminated by the same slit, will be seen side by side. The distance apart of the centers of these two spectra depends upon the separation of the two halves of the collimator objective, and obviously their edges may be made to touch simply by changing the length of the slit. A small circular diaphragm was placed in the focal plane of the observing telescope. Upon looking into the eyepiece, a circle of practically monochromatic light appeared, whose upper half was illuminated by the light which passed through the upper half of the collimator objective, and whose lower half by the light which passed through the lower half of the collimator objective. The approximate wavelength of this light could be taken from the graduated circle of the spectrometer. If the areas of the two halves of the objective were equal, the two halves of this colored circle of the light would be equally brilliant and the line of demarcation would disappear. The collimator objective was provided with a cap having two rectangular apertures, the upper one of constant area and the lower one of the same width, but of a length which could be varied with a micrometer screw. The reading of this screw gave at once the relative areas of the two openings.

The sample of glass to be tested was placed on a support immediately in front of the upper opening, and the lower one was closed until the circle appeared uniformly illuminated. The amount of light transmitted was evidently the ratio of the areas of the two openings. No account was taken of the loss by reflection at normal incidence. Table I gives the values of the coefficient of absorption for 100 mm for the four kinds of glass tested. Each determination is the mean of five made at different times. Though the separate results agree fairly well, yet I suspect large constant errors due to causes to be explained later; the relative values are, I believe, fairly accurate. The chief difficulty was in securing uniform illumination of the collimator objective. This was increased as I used an ordinary single achromatic photographic lens of rather short focus; but even this would have been much less troublesome had I had a heliostat whose reflecting surfaces were optical flats. I finally illuminated the slit with the diffused light reflected from a piece of white paper.

The Fraunhofer lines caused no trouble, as the spectrum was made so impure as to blot them out entirely. A physiological phenomenon, however, caused the greatest difficulty. It is evident that, if the adjustments are so made that the two spectra are tangent, the slightest change in focus will destroy the adjustment. Now, the eye seems to dislike the condition of tangency, and, as the two spectra came near together, the eye would suddenly change its focus and they would overlap. I believe this could be much improved by using a collimator of very small angular aperture.

TABLE I

	$\lambda=486$	$\lambda=434$	$\lambda=410$
Old glass	0.46	0.23	0.07
3670	0.89	0.65	0.52
3892	0.82	0.72	0.58
3631	0.89	0.73	0.61

The difference between the coefficients of absorption of the new glasses was too small to be of any moment, so I selected No. 3670, since this glass gave the greatest dispersion of the three. The indices of refraction of this glass, interpolated from values furnished me by Mr. Brashear, are 1.6287 for $\lambda=486$, 1.6389 for $\lambda=434$, and 1.6453 for $\lambda=410$. For the old prism $n=1.728$ for $\lambda=434$. With these data we find the most suitable prism-angle to be 62° 48′. The effective aperture of the collimator was about 25 mm, and as I expected to work between the limits $\lambda=4600$ and $\lambda=4100$, I determined the sizes of the prisms so that they would transmit a clear beam of 30 mm diameter between the above wave-length limits. This gave for the sizes of the faces of the prisms:

No. 1 = 30 mm × 58 mm
No. 2 = 30 mm × 61 mm
No. 3 = 30 mm × 66 mm

leaving but small leeway from theory. The prisms were ordered from Mr. Brashear and were found most satisfactory. Computing all losses, we find that the intensity of light ($H\gamma$) transmitted

through the two dense-flint prisms is 0.263, and through the three light ones, 0.338. The dispersion along the plate was, for the old, 0.048 mm per Ångström unit, and for the new, 0.054 mm. From this it is evident that the light efficiency of the new in terms of the old is $\frac{0.338\times 0.048}{0.263\times 0.054}=1.15$, or a gain of 15 per cent. This, combined with the gain of 12 per cent. in dispersion, seemed to indicate a very decided improvement, especially when it is evident that the gain on the violet side of $H\gamma$ would be much more marked.

By this time the money originally appropriated by the board of trustees for the new prisms was gone, except just enough to purchase the optical parts, and I was compelled to build the mounting myself. The prisms were fastened in a fixed position at minimum deviation for $H\gamma$. The Potsdam method of using the light reflected from the front face of the first prism was used for following. The following telescope was of ample aperture to transmit the full beam, and was provided with a single spider-web at right angles to the image of the slit, thus allowing the entire length of the slit to be uncovered during the exposure on the star whose image was kept bisected by the spider-web. The cross-wire was illuminated by a small incandescent lamp, controlled by a rheostat in easy reach of the observer. Before reaching the cross-wire the light passed through two thicknesses of blue glass, and a third piece was placed between the eyepiece and the eye. The new and the old instruments were carefully tested, and, so far as I could tell, confirmed the above figures for $H\gamma$, though 15 per cent. is not easy to detect in this way. Suffice it to say that satisfactory spectrograms have been secured in 60 minutes of η *Piscium*, whose photographic magnitude is 5.02.

COMPARISON APPARATUS

The comparison apparatus carried a rocking arm to one side of which was fastened the spark terminals, and to the other the Plücker tube. A spring catch enabled either tube or spark to be brought into the axis of collimation of the telescope without disturbing the position of the condensing lens which concentrated the light on the slit. The capillary of the Plücker tube and the axis of the spark

were both parallel to the slit. Between tube or spark and condensing lens was placed a piece of ground glass—a suggestion of the late Professor Keeler's.

During the exposure on the star the entire apparatus could be turned on a hinge so as to be out of the way. When the work was first started, the iron and hydrogen were mounted on separate supports; no condensing lens was used for the hydrogen, whose capillary was placed at right angles to the slit. These plates showed a small but persistent difference of the artificial $H\gamma$ relative to the iron lines, which practically disappeared with the newer apparatus. The end of the collimator carried an arm which could be turned down on the slit so as to cover up that portion occupied by the star, leaving two narrow openings on each side. This occulting bar was rather wide, so that the plates showed quite a gap of clear glass between the star spectrum and the comparison spectrum. The camera carried an occulting bar, as described by Campbell, the bar covering up the more intense comparison lines during part of the exposure. The comparison spectrum was photographed both at the beginning and the end of the exposure on the star, except in a few cases, where this latter was under two minutes. During an evening's work the spectroscope was inclosed in a box of $\frac{1}{4}$-inch pine, heavily oiled and varnished, on the inside of which were coils for electric heating. These coils were used in only a few of the earlier plates. Temperatures were read at the beginning and end, or if the plates followed rapidly, only at the beginning. The record of the observations is given in Table II. The temperatures, where incomplete, were filled out from the plates either immediately preceding or following the one listed.

TABLE II

RECORD OF PHOTOGRAPHS

Plate No.	Date of Photograph	Name of Star	Focus	Prism Temp. Begin	Prism Temp. End	Box Temp. Begin	Box Temp. End	Sky	Exposure	Sid. Time of End	Remarks
534	Nov. 2, 1898	*α Cassiopeiae*	25.9	..	..	..	..	Hazy	45^m	$2^h\ 40^m$	Temperature of air 37°5 Temperature of prisms 43°. Comparison $H\gamma$. Potsdam reduction, using two negatives together.
535	" 7, "	"	26.2	..	..	..	..	Clear	35	1 45	Prism temperature 46°. Comparison as in 534
536	" 11, "	"	25.7	..	..	..	..	"	40	1 35	Temperature of air 33°. Prism temperature 37°. Comparison as above.
539	" 20, "	"	26.1	..	..	..	..	"	40	1 40	Temperature of air 42°5. Prism temperature 46°. Comparison as above.
540	Dec. 8, "	"	24.9	..	..	..	..	"	40	2 05	Air temperature 12°5. Prism temperature 18.° Comparison as above.
562	Jan. 22, 1899	*α Aurigae*	25.7	..	..	..	..	L't cl'ds V. thick	60	6 25	Lantern slide plate. Comparison *Fe* and *H*. Air T=35°.
563	" 25, "	"	25.7	..	..	..	..	"	60	6 35	Lantern slide plate. Comparison as above. Air temperature, 33°.
564	" 29, "	"	24.9	..	..	..	..	Clear	60	6 55	*H* and *Fe* comparison. Lantern slide plate. Air temperature 13° to 10°.
572	May 13, "	*η Boötis*	26.7	59°0	58°3	..	..	"	45	13 05	*Fe* and *H*
581	" 24, "	"	27.0	68.0	66.0	..	..	V. Hazy	60	13 50	"
585	June 2, "	"	27.4	73.0	71.0	..	..	Clear	40	15 30	"
586	" 10, "	"	27.0	..	..	..	..	"	60	15 10	" Air temperature, 65°.
587	" 17, "	"	27.1	..	..	..	..	"	60	15 35	*Fe* and *H*. Air temperature, 68°.
588	" 18, "	"	27.1	..	..	..	..	"	35	15 05	*Fe* and *H*. Air temperature, 70°.
591	" 29, "	"	27.0	..	..	..	..	"	45	16 15	"
595	Jan. 21, 1900	*κ Geminorum*	25.7	30	28	..	..	"	65	9 10	"
601	" 26, "	"	25.3	19.5	18.0	..	..	"	60	7 45	"
602	" 28, "	"	25.1	16	12	..	..		60	7 32	"
603	Feb. 13, "	"	25.6	30	29.5	..	..	"	60	7 40	"
604	" 13, "	*o Ursae Majoris*	25.6	29.5	28.5	..	..	"	60	9 40	" Took out following eyepiece during exposure; moved hard.
605	" 19, "	*κ Geminorum*	25.3	23	21	..	..	"	60	7 50	
606	" 19, "	*o Ursae Majoris*	25.3	21	21	..	..	"	40	9 20	*Fe* and *H*; and seeing very bad on 605 and 606
611	Mar. 21, "	"	25.7	31	31	..	..	"	50	9 30	*Fe* and *H*.
613	" 22, "	"	26.4	47.5	46.0	..	..	"	50	8 25	" Seeing v. good.
615	" 31, "	"	26.4	42	40	..	..	"	50	9 35	"
617	Apr. 4, "	"	26.4	41	39	..	..	"	50	9 30	"
											All above plates taken with battery of two dense flint prisms, covered with bag of velvet and felt. All following plates taken with battery of three prisms, and measured and reduced as described
681	Apr. 20, 1902	*α Ursae Majoris*	24.9	62	61.5	61	60.5	V. hazy	45	12 45	
682	" 22, "	"	24.3	—	77	77	76	Hazy	40	11 05	Heating coils used.
683	" 23, "	"	25.1	55	55	54	55	Clear	45	11 10	Light clouds passing.
685	" 23, "	*η Boötis*	25.1	53	53	52	51	"	30	14 40	
686	" 23, "	*α Boötis*	25.1	—	—	—	—	"	4	14 55	
687	" 24, "	*α Ursae Majoris*	25.1	62.5	62	61	61	V. Clear	30	11 00	
690	" 27, "	"	25.1	62	63	60	60	Clear	30	11 10	Seeing fine.

TABLE II—*Continued*

Plate No.	Date of Photograph	Name of Star	Focus	Prism Temp.		Box Temp.		Sky	Exposure	Sid. Time of End	Remarks
				Begin	End	Begin	End				
692	Apr. 27, 1902	η Boötis	25.1	57°	56°	55°	54°	Clear	25m	14h 35m	
696	" 30, "	β Virginis	24.9	62	62	61	61	"	70	13 30	Induction coil broke.
699	May 2, "	η Boötis	24.3	74	73.5	73	74	"	25	14 40	Heating coils used.
700	" 2, "	α Boötis	24.3	—	—	—	—	"	3	15 08	
706	" 8, "	β Virginis	24.7	69.5	69.5	68.5	68	"	75	13 45	One heating coil used.
707	" 8, "	η Boötis	24.7	69	69	70	68	"	30	14 05	One heating coil used; second coil 5 minutes.
709	" 9 "	β Virginis	25.1	53.5	54	52.5	53	"	75	13 20	One heating coil.
710	" 9, "	η Boötis	25.1	53.5	53.5	52	52.5	"	30	14 35	One and two coils.
711	" 9, "	α Boötis	25.1	—	—	—	—	"	4	14 53	One coil.
713	" 12, "	ι Virginis	24.3	74	72	72	70	"	75	14 40	One and two coils.
714	" 12, "	α Boötis	24.3	—	—	—	—	"	3	14 55	One coil.
716	" 26, "	β Virginis	24.7	67	66.5	66	65	"	70	13 30	One coil part time.
717	" 28, "	"	24.7	58	57.5	68.5	68	"	70	13 40	One coil part time.
719	June 9, "	ε Virginis	24.7	70.5	68	69.5	69	"	60	14 40	
720	" 9, "	α Boötis	24.7	68	—	67	—	"	4	15 24	One coil.
722	" 11, "	ε Virginis	24.1	81	80.5	80	80	"	60	14 35	One coil part time.
723	" 16, "	"	24.5	72.5	72.5	72	71	"	60	14 45	One coil part time
725	" 21, "	"	24.7	65.5	—	64.5	—	"	60	15 10	One coil part time.
726	" 21, "	α Boötis	24.7	—	—	—	—	"	4	15 30	
754	July 22, 1903	β Draconis	24.5	—	72	72	71	V. clear	50	18 30	
756	" 23, "	δ Draconis	24.5	74	74	75	73	"	75	19 20	
758	" 24, "	β Draconis	24.3	81	80	81	79	Hazy	75	17 45	
761	" 31, "	"	24.7	68	67	68	66	Clear	60	19 00	
764	Aug. 7, "	"	24.7	64	—	64	—	"	60	19 20	Seeing very bad.
765	" 7, "	δ Draconis	24.7	—	62	—	61	"	75	20 55	Clouds at end.
766	" 9, "	β Draconis	24.7	—	73	74	72	"	45	18 35	Light clouds.
768	" 11, "	δ Draconis	24.5	68	—	70	—	"	60	19 15	Through clouds.
770	" 12, "	ε Cygni	24.5	65	64	64	64	L't cl'ds	35	20 40	
771	" 16, "	δ Draconis	24.5	74	74	74	72	Clear	75	19 20	
772	" 16, "	ε Cygni	24.5	72	71	71	70	"	35	20 45	
774	" 17, "	δ Draconis	24.5	76	74	76	74	"	70	19 20	
775	" 17, "	ε Cygni	24.5	74	73	73	72	"	40	20 45	
776	" 17, "	η Pegasi	24.5	72	70	71	69	Hazy	60	22 35	
780	" 20, "	ε Cygni	24.5	—	—	—	—	Clear	40	20 50	
781	" 20, "	η Pegasi	24.5	68	66	67	65	"	60	22 30	
782	" 21, "	γ Cygni	24.5	76	76	76	76	"	20	19 20	
783	" 21, "	ε Cygni	24.5	75	74	75	73	"	45	20 45	
784	" 21, "	η Pegasi	24.5	74	73	73	72	"	60	22 30	
785	" 23, "	γ Cygni	23.9	86	—	86	—	"	20	20 10	
787	Sept. 1, "	χ Draconis	24.7	68	68	68	67	Hazy	60	20 05	
788	" 1, "	γ Cygni	24.7	68	66	67	65	Clear	25	21 00	
789	" 1, "	η Pegasi	24.7	66	64	64	62	Hazy	60	22 35	
790	" 2, "	χ Draconis	24.5	73	73	73	72	V. hazy	60	19 45	
792	" 6, "	γ Cygni	24.7	65	66	66	—	Clear	25	19 55	
793	" 6, "	η Pegasi	24.7	66	64	64	63	"	60	21 53	Clouds at end.
794	" 12, "	γ Cygni	24.1	80	—	80	—	"	30	20 25	
799	" 24, "	ε Pegasi	25.3	54	53	54	52	"	60	21 45	
800	" 24, "	δ Cephei	25.3	53	51	52	50	"	75	00 00	
802	" 25, "	ε Pegasi	24.9	63	62	62	61	V. sm'ky	75	22 00	
803	" 25, "	δ Cephei	24.9	62	59	61	58	"	75	00 00	
807	Oct. 12, "	α Arietis	—	53	50	52	50	Clear	60	2 15	Windows badly dewed; objective O. K.
808	" 18, "	ε Pegasi	25.3	49	—	59	—	"	75	23 05	
811	" 19, "	"	25.1	58	58	58	57	Hazy	75	23 15	
812	" 24, "	"	25.7	41	40	40	40	Clear	75	23 30	
814	" 24, "	α Arietis	25.7	—	39	—	38	"	60	2 05	Charged batteries during exposure.
816	" 25, "	"	25.5	48	48	48	48	"	60	1 45	
819	" 26, "	"	25.5	35	34	34	34	"	60	3 10	
820	" 28, "	"	25.8	44	44	44	44	"	60	1 25	
848	Mar. 23, 1904	β Geminorum	23.3	40	40	40	40	"	30	8 30	
852	" 28, "	"	23.9	36	36	36	36	V. hazy	15	9 05	Seeing very bad.
857	Apr. 4, "	"	23.7	41	41	41	41	"	30	9 45	April 18 found camera focus 1 mm out.
858	" 5, "	"	23.3	53	53	53	53	"	30	9 20	
860	" 14, "	"	23.7	42	—	42	42	Clear	25	10 05	

TABLE II—*Continued*

Plate No.	Date of Photograph	Name of Star	Focus	Prism Temp. Begin	Prism Temp. End	Box Temp. Begin	Box Temp. End	Sky	Exposure	Sid. Time of End	Remarks
861	Apr. 14, 1904	γ *Leonis*	23.7	41	41	41	40	Clear	50^m	11^h 35^m	
862	" 16, "	"	23.7	37	38	37	37	V. Clear	45	11 05	
864	" 19, "	"	24.0	33	34	33	33	Clear	60	11 20	
668	May 5, "	"	22.5	72	70	72	70	——	60	11 45	
870	" 9, "	"	23.0	60	59	59	59	Clear	60	12 15	
871	" 10, "	α *Boötis*	23.3	50	50	50	50	"	4	13 16	
872	" 10, "	ε *Boötis*	23.3	50	49	50	49	——	45	14 45	Through clouds.
876	" 20, "	"	25.0	58	58	58	58	——	30	15 50	
877	" 27, "	"	23.7	65	65	65	64	Clear	45	14 25	
878	" 27, "	α *Serpentis*	23.7	65	63	64	61	"	60	15 40	
879	" 27, "	ζ *Herculis*	23.7	63	60	61	59	"	45	16 45	
881	" 28, "	α *Boötis*	23.7	66	—	66	—	"	4	13 15	
882	" 28, "	ε *Boötis*	23.7	66	66	66	65	"	45	14 25	
884	" 28, "	ζ *Herculis*	23.7	64	62	62	61	"	45	16 50	
885	June 3, "	ε *Boötis*	23.1	81	—	81	—	Clouds	45	14 30	
887	" 9, "	ζ *Herculis*	23.9	64	63	63	62	V. hazy	45	16 55	Seeing bad.
889	" 11, "	α *Serpentis*	23.5	69	69	70	68	——	60	15 55	
892	" 12, "	"	23.3	73	72	72	71	Clear	60	15 45	
895	" 16, "	"	23.7	—	66	—	66	"	70	15 50	
896	" 16, "	ζ *Herculis*	23.7	66	65	66	64	——	45	16 55	Heavy fog low down.
897	" 17, "	α *Serpentis*	23.5	70	70	70	69	Clear	60	15 50	
898	" 17, "	ζ *Herculis*	23.5	70	68	69	67	"	45	17 00	
903	Sept. 10, "	β *Cygni*	24.3	73	72	73	72	——	75	21 05	
904	" 13, "	"	24.3	—	70	—	70	V. hazy	75	20 40	
905	" 14, "	"	24.9	58	58	58	58	Clear	75	21 20	
906	" 15, "	"	24.9	60	60	59	58	——	75	20 45	Clear at beginning, hazy at end.
907	" 17, "	"	24.3	74	—	74	73	V. hazy	75	21 15	
909	Oct. 15, "	δ *Andromedae*	25.3	48	48	48	48	Clear	60	0 45	
910	" 15, "	γ *Andromedae*	25.3	—	—	—	—	"	45	2 00	
913	" 17, "	δ *Andromedae*	25.0	60	58	59	57	V. smoky	60	0 30	
914	" 18, "	"	24.0	59	58	59	58	"	60	0 30	
916	" 21, "	"	24.5	45	46	45	46	Clear	60	0 55	
917	" 24, "	"	24.3	52	52	52	52	Hazy	60	0 10	
920	" 29, "	γ *Andromedae*	24.3	48	47	47	46	——	45	1 35	Clear but smoky.
922	" 29, "	α *Persei*	24.3	45	45	44	44	Clear	10	3 00	
925	" 30, "	η *Cassiopeiae*	24.5	45	44	45	44	V. clear	60	0 20	
926	" 30, "	γ *Andromedae*	24.5	44	43	44	42	"	45	1 20	
927	" 30, "	γ *Persei*	24.5	43	42	42	41	"	45	2 20	
928	" 30, "	α *Persei*	24.5	42	41	41	40	"	10	2 44	
930	" 31, "	η *Cassiopeiae*	24.5	45	45	45	45	Smoky	60	0 15	
931	" 31, "	γ *Andromedae*	24.5	45	44	45	43	V. smoky	45	1 15	
932	" 31, "	γ *Persei*	24.5	44	42	43	42	"	45	2 20	
936	Nov. 6, "	η *Cassiopeiae*	24.7	40	40	40	40	Clear	60	0 20	
938	" 6, "	γ *Persei*	24.7	39	40	39	38	V. clear	45	2 15	
939	" 6, "	γ *Andromedae*	24.7	40	39	38	38	"	45	3 15	
940	" 6, "	α *Persei*	24.7	—	—	—	—	——	10	3 35	
941	" 11, "	η *Cassiopeiae*	25.1	36	36	36	36	V. clear	60	0 50	
942	" 11, "	γ *Persei*	25.1	36	36	36	35	"	45	1 50	
943	" 11, "	α *Persei*	25.1	36	36	35	35	"	10	2 18	
945	" 22, "	η *Cassiopeiae*	24.5	45	46	45	44	Clear	60	0 55	
946	" 22, "	γ *Persei*	24.5	—	—	—	—	"	45	2 40	Light clouds at end.
947	" 22, "	α *Persei*	24.5	—	42	—	40	"	10	3 10	
948	" 30, "	η *Piscium*	25.1	30	30	30	28	"	75	2 00	
949	" 30, "	α *Tauri*	25.1	29	28	28	27	"	30	3 25	
951	Dec. 14, "	"	25.5	18	18	—	—	"	30	3 35	
953	" 30, "	η *Piscium*	24.7	39	37	38	37	"	75	2 55	
954	" 30, "	α *Tauri*	24.7	37	38	37	37	"	30	3 40	
956	" 31, "	η *Piscium*	24.7	45	44	45	43	"	75	2 55	
957	" 31, "	α *Tauri*	24.7	44	44	43	43	"	30	3 40	
960	Jan. 1, 1905	η *Piscium*	24.3	50	49	50	48	"	75	2 40	
961	" 1, "	α *Tauri*	24.3	49	49	48	48	"	30	3 25	

TABLE II—*Continued*

PLATES OF *Venus*

Plate No.	Date of Photograph	Focus	Prism Temp. Begin	Prism Temp. End	Box Temp. Begin	Box Temp. End	Sky	Exposure	Sid. Time of End	Remarks
651	Nov. 27, 1901	25.9	35	—	—	—	Clear	30s	21h 40m	
658	" 30, "	25.5	46	—	—	—	V. smoky	60		Sid. T. end about 22h 00.
660	Dec. 4, "	26.0	33	—	—	—	Clear	40	22 23	
661	" 15, "	26.7	15	—	—	—	"	45	23 00	
666	" 30, "	26.0	38	—	—	—	"	45	0 15	
668	" 31, "	26.0	42	—	—	—	"	45	23 50	Position circle, 91°.
673	Jan. 4, 1902	26.0	28	—	—	—	"	45	0 25	
676	" 6, "	26.0	39	—	—	—	Smoky	45	0 30	
689	Apr. 26, "	25.1	46	—	—	—	Clear	30		4:30 A. M. Mean Time.
695	" 29, "	25.1	—	—	—	—	"	6	20 20	
705	May 5, "	24.3	—	—	—	—	"	60	19 45	
731	Apr. 10, 1903	24.7	65	—	—	—	"	90	8 40	Position circle, 92°.
734	" 18, "	25.0	58	—	—	—	"	180		Position circle, 92°, 7:30 P. M., Mean Time.
747	July 5, "	23.8	84	—	—	—	——	120		Position circle, 91°, 8:00 P. M.
748	" 6, "	23.8	87	—	—	—	——	45	15 25	
749	" 7, "	23.8	84	—	—	—	——	60	15 00	
751	" 8, "	23.8	84	—	—	—	——	90	15 00	
952	Dec. 30, 1904	24.7	—	—	40	—	——	45	0 25	
955	" 31, "	24.7	—	—	46	—	——	40	.—	5:30 P. M., Mean Time.
962	Jan. 16, 1905	25.3	27	—	—	—	Clear	30	.—	5:20 " " "
964	" 26, "	25.5	20	—	—	—	——	35	.—	5:40 " " "
965	Feb. 4, "	25.5	—	—	—	—	——	—	.—	6:55 " " "
966	" 7, "	25.5	20	—	—	—	——	30	.—	5:30 " " "
967	" 10, "	25.5	20	—	—	—	——	30	.—	5:45 " " "
968	" 15, "	27.0	8	—	—	—	——	30	.—	6:10 " " "

ADOPTED WAVE-LENGTHS OF COMPARISON LINES

The wave-lengths of the comparison lines as finally adopted are given below in Table III:

TABLE III

λ	m	λ	m	λ	m
4181.92.....	40.654	4227.61....	43.557	4340.63....	50.001
4187.22.....	41.000	4260.66....	45.544	4383.72....	52.217
4187.97.....	41.049	4271.93....	46.202	4404.93....	53.264
4202.20.....	41.966	4308.07....	48.244	4415.30....	53.766
4219.52.....	43.057	4325.94....	49.218		

The wave-lengths of the iron lines were at first taken from Rowland's tables, but later on they were corrected by the values published by Kayser.[1] The lines at $\lambda=4187.971$ and $\lambda=4308.073$ could never be made to fit with the other iron lines on the star plates, and as this observatory has a five-foot concave grating spectroscope, and as their wave-lengths were not given by Kayser, I determined

[1] *Astrophysical Journal*, 13, 332, 1901.

to measure their wave-lengths, interpolating from those given by Kayser. Five plates were taken, and the entire list of thirteen iron lines was measured. The eleven lines given by Kayser were regarded as known, and an interpolating curve of the second degree passed through them, the constants of this curve being determined by the method of least squares. An unknown correction, $\Delta\lambda$, was then given to the approximate values λ 4187.94 and λ 4308.08, and its value computed for these lines, as were also the wave-lengths of the known lines. A different curve was computed for each plate. The values of $\Delta\lambda$ and the residuals of the known lines are given below in Table IV:

TABLE IV

λ	$\Delta\lambda$					
	Plate No. 1	Plate No. 2	Plate No. 3	Plate No. 4	Plate No. 5	Mean
4181.918..........	+0.001	−0.008	+0.006	−0.005	−0.014	−0.004
4187.221..........	−0.003	−0.010	−0.006	−0.005	−0.004	−0.006
4187.94...........	+0.022	+0.032	+0.030	+0.040	+0.029	+0.031
4202.195..........	−0.009	−0.005	−0.002	±0.000	−0.005	−0.004
4219.523..........	+0.009	−0.017	+0.024	+0.006	+0.021	+0.009
4227.606..........	+0.008	+0.021	−0.024	+0.015	+0.018	+0.008
4260.656..........	−0.002	+0.001	−0.001	−0.005	−0.001	−0.002
4271.933..........	+ 0.003	−0.001	+0.005	−0.005	±0.000	±0.000
4308.08...........	−0.009	−0.002	−0.011	−0.002	−0.013	−0.007
4325.941..........	−0.013	−0.002	+0.001	−0.004	−0.001	−0.004
4383.724..........	+0.003	−0.018	−0.007	+0.002	−0.021	−0.008
4404.929..........	+0.006	+0.005	+0.017	+0.002	+0.016	+0.009
4415.301..........	−0.005	+0.013	−0.011	−0.002	+0.004	±0.000

Applying these corrections, we find the values λ4187.971 and λ4308.073, as against λ4187.943 and 4308.081 as given by Rowland. The values given in Table III were used after April 1, 1903; the earlier plates were not corrected, as the change was too small to be of any moment.

METHOD OF MEASURING THE PLATES

The plates were all measured upon a Zeiss comparator reading directly to 0.001 mm and by estimation to 0.0001 mm. The division errors were determined over the portion of the scale used, by a method slightly modified from that published by Dr. Gill in *Monthly Notices*, **49**, 105.

Each plate was first carefully examined and, if found satisfactory, was measured and reduced; if unsatisfactory, it was rejected before measuring. In only one case was a plate rejected after measuring. In this case an error in the exposures on the iron comparison was suspected before measuring. This plate was reduced as far as the comparison lines only, $H\gamma$ did not agree with the iron lines, and the plate was then rejected. The plates were placed on the table of the measuring engine so that $H\gamma$ fell very near to scale reading 50, which could be easily done within a few thousandths of a millimeter: Four to six pointings were then made upon the artificial $H\gamma$, and the plate was run to one end, and star lines and comparison lines were measured as they came into the field of view, three pointings on each star line and four pointings on each iron line. As soon as $H\gamma$ was reached, four or six more pointings were made upon it, and the measuring was continued until the end of the plate was reached. The instrument was then set back to $H\gamma$, and four or six more pointings were made. On all of the artificial lines the pointings were equally divided on both sides of the star spectrum. After a short rest, the observer remeasured the plate with the violet end on the opposite hand; the agreement of the three measures of $H\gamma$ served as a check on the work, and in no case was any progressive shift detected, such as found by Curtis.[1] Division error and error of runs were then applied to 0.0001 mm to the mean of the pointings on each line, after which the last place of decimals was dropped. The difference of the mean of the three settings on $H\gamma$ and 50 was then applied to all lines to reduce to the common zero, $H\gamma = 50.000$.

METHOD OF REDUCTION

On a lantern-slide plate of the solar spectrum, twenty-six carefully selected lines were identified with lines on Rowland's map. The distances of these lines from $H\gamma$ were measured on three different days in two positions of the plate. Through these points the following curve was passed:

$$m = 131.655 \text{ mm} - \frac{[5.1009292]}{\lambda - 2795.54} .$$

Here m is the micrometer setting corresponding to any line of wave-

[1] *Lick Observatory Bulletin* No. 62.

length λ when $H\gamma$ reads 50. The residuals were all small, only two of the 26 being 0.004 mm. Later on Mr. Maag computed the curve

$$m=159.388-\frac{[3.8956145]}{(\lambda-3098.00)^{0.6}},$$

which reduced Σvv from 66 to 29. This curve has, however, not been used, as it gave when tried on a few plates, practically identical results with the simpler curve. With this simpler curve the values of m for each comparison line were computed and are given in Table III. A list of 120 lines was then measured on the solar tandard, and their character was marked. These lines were measured on two different days in both positions of the instrument and reduced to a common zero, $H\gamma=50$, after which the average value of m was tabulated. Thus the m's in this table of solar lines were determined by measurement directly, and not by computation from their wave-lengths. This was done in the hope of avoiding the uncertainty in the wave-length to be assigned to a "blend."

If a star plate could be taken under exactly the same conditions as the solar standard, it is evident that the difference of the distance of any line on the star negative from the artificial $H\gamma$, subtracted from the corresponding reading taken from the table of solar lines, would give at once its velocity-displacement. But as this can never be done, it becomes necessary to apply corrections due to these changed conditions. In order to determine these corrections from the measures of the fourteen lines of Table III, let us give to the constants of the Hartmann-Cornu interpolation formula small unknown corrections Δm_0, Δc, and $\Delta\lambda_0$. The setting on any artificial line is then given by the equation

$$m=m_0+\Delta m_0+\frac{c+\Delta c}{\lambda-(\lambda_0+\Delta\lambda_0)}.$$

From this it readily follows that the difference of any observed value of m and its value taken from Table II will be given by the equation

$$\text{C.}-\text{O.}=x+(m-47)y+\frac{(m-47)^2}{10}z.$$

Here x, y, and z are unknown, and the value of m used in computing

the coefficients may be taken from Table III. This equation may be more simply written

$$C.-O.=x+by+cz\ .$$

Now, the same artificial lines being measured on all plates, b and c are always the same. Moreover, as soon as x, y, and z become known, this equation worked backward gives the correction necessary to reduce the star lines to the solar standard. The coefficients b and c have been computed once for all and their values added to the table of 120 solar lines.

To determine the values of x, y, and z, we make use of the comparison lines. Each line gives an equation of the above form, and the fourteen equations may be very easily and rapidly reduced by the method of least squares, as follows: Forming the normals we have—

$$\begin{aligned} Nx+(\Sigma b)y+(\Sigma c)z &= \Sigma\ (C.-O.)\ , \\ (\Sigma b)x+(\Sigma b^2)y+(\Sigma bc)z &= \Sigma b(C.-O.)\ , \\ (\Sigma c)z+(\Sigma bc)y+(\Sigma c^2)z &= \Sigma c(C.-O.)\ . \end{aligned}$$

Solving these, we find—

$$\begin{aligned} x &= \alpha_1\Sigma(C.-O.)+\beta_1\Sigma b(C.-O.)+\gamma_1\Sigma c(C.-O.)\ , \\ y &= \alpha_2\Sigma(C.-O.)+\beta_2\Sigma b(C.-O.)+\gamma_2\Sigma c(C.-O.)\ , \\ z &= \alpha_3\Sigma(C.-O.)+\beta_3\Sigma b(C.-O.)+\gamma_3\Sigma c(C.-O.)\ . \end{aligned}$$

Since the same series of artificial lines are always observed, the Greek letters are always the same and their values may be computed once for all. It is only necessary, therefore, to form the quantities $\Sigma(C.-O.)$, $\Sigma b(C.-O.)$, and $\Sigma c(C.-O.)$ anew for each plate. This can be very easily and rapidly done with Crelle's Table. Then substituting their values, using four-place logarithms, the values of x, y, and z are rapidly computed. Ten plates give average probable errors of x, y, and z, respectively as $r_x=\pm 0.6$, $r_y=\pm 0.08$, and $r_z=\pm 0.02$. The maximum values of the quantities themselves may be taken as $x=75$, $y=25$, and $z=1.5$, the unit being the thousandth of a millimeter; z might possibly be dropped and the reduction correspondingly simplified. I have, however, preferred to keep it. The values of x, y, and z were checked by substituting their values in the above equation and computing the value of (C.—O.) for each artificial line. I give below a complete example of this reduction. The heavy-faced figures can be printed once for all, the light-faced

figures must be computed for each plate. Mr. Maag tells me that this computation can be easily made in half an hour. It should be noted that any shrinkage of the film, error of measuring engine, or other source of error is completely eliminated, provided only it can be represented by an equation of the second degree. The lines were all given equal weight, except where it was obviously a case of faulty identification, in which case the doubtful line was rejected. It is hoped at some future date to publish the complete reduction sheets of each plate as a contribution from this observatory, but at present we have no funds for such a purpose. Should that be done, the lines rejected will of course appear. It is impossible, however to give them here.

EXAMPLE

Reduction of Iron Lines. Plate No. 806. Star α *Cassiopeiae*. Violet Left.

λ	Computed m	Observed m	C.−O. n[1]	$m-47$ b	$\frac{(m-47)^2}{10}$ c	bn[1]	cn[1]	by[1]	cz[1]	Correction $=x+by+cz$[1]
4181.92...	40.654	40.747	−93	−6.35	+4.03	+591	−375	−64	+1	−93
4187.22...	41.000	41.088	−88	−6.00	+3.60	+528	−317	−60	+1	−89
4187.97...	41.049	41.138	−89	−5.95	+3.54	+530	−315	−60	+1	−89
4202.20...	41.966	42.044	−78	−5.03	+2.53	+392	−197	−50	+1	−79
4219.52...	43.057	43.127	−70	−3.94	+1.55	+276	−108	−40	0	−70
4227.61...	43.557	43.623	−66	−3.44	+1.18	+227	− 78	−35	0	−65
4260.66...	45.544	45.590	−46	−1.46	+0.21	+ 67	− 10	−15	0	−45
4271.93...	46.202	46.239	−37	−0.80	+0.06	+ 30	− 2	− 8	0	−38
4308.07...	48 244	48.261	−17	+1.24	+0.15	− 21	− 3	+12	0	−18
4325.94...	49.218	49.224	− 6	+2.22	+0.49	− 13	− 3	+22	0	− 8
4340.63...	50.001	50.000	+ 1	+3.00	+0.90	+ 3	+ 1	+30	0	± 0
4383.72..	52.217	52.193	+24	+5.22	+2.72	+125	+ 65	+52	+1	+23
4404.93...	53.264	53.231	+33	+6.26	+3.92	+207	+129	+63	+1	+34
4415.30...	53.766	53.727	+39	+6.76	+4.57	+264	+178	+68	+1	+39
	Sums		−493			+3206	−1035			

Log. Σn.....	2.6928_n	Log. Σn....	2.6928_n	Log. Σn......	2.6928_n
	9.3008		**7.2859**		**8.7819_n**
Sum.......	1.9936_n	Sum........	9.9787_n	Sum..........	1.4747
α...........	−98.6	α'..........	− 0.95	α''...........	+29.83
Log. Σbn....	3.5059	Log. Σbn....	3.5059	Log. Σbn......	3.5059
	7.2859		**7.5378**		**5.7046**
Sum........	0.7918	Sum........	1.0437	Sum..........	9.2105
β...........	+ 6.2	β'..........	+11.03	β''...........	+ 0.16
Log. Σcn....	3.0148_n	Log. Σcn....	3.0148_n	Log. Σcn.....	3.0148_n
	8.7819		**5.7046**		**8.4592**
Sum........	1.7967	Sum........	8.7194_n	Sum..........	1.4740_n
γ...........	+62.6	γ'..........	− 0.05	γ''...........	−29.79
$\alpha+\beta+\gamma=x$..	−29.8	$\alpha'+\beta'+\gamma'=y$	+10.03	$\alpha''+\beta''+\gamma''=z$	+ 0.20

[1] These numbers are in units of last figure in column of m's, or in thousandths of a millimeter.

CURVATURE

The curvature of the lines was determined experimentally by placing two photographs of the iron spectrum film to film, the violet end of one opposite the red end of the other, and then shifting the plates until the extremities of the curved lines came in contact. This gave us as the equation of the line $x=0.0085$ mm y^2. The value of the constant, computed from the known optical constants of the instruments, came out 0.0080 mm. The agreement was considered satisfactory. By the method of following, the star spectrum was seldom midway between the two halves of the iron spectrum, so that the correction to the final velocity was computed by

$$\Delta v=-[1.0475](z_1^2-z_0^2) \ ,$$

where z_1 and z_0 are respectively the distances of the comparison spectrum and the star spectrum from the line midway between the two parts of the iron spectrum, and were measured for each plate.

DISCUSSION OF THE RESULTS

The mean velocity for each star, as given in Table V, except of η *Piscium* and those having fewer than five nights' work, was subtracted from the velocity derived for each plate. This gave 129 residuals, the sum of whose squares came out 1005.59. Treating these as residuals from the mean of a single directly measured quantity, we find the probable error of a single plate to be $0.67\times(1005.59 \div 1.28)^{\frac{1}{2}}=\pm 1.88$ km per sec., or the probable error of the mean of five to be ± 0.8 km per sec. This process is open to criticism and is apt to give too small a value for the probable error. But I believe results derived in this way are much nearer the truth than values of the probable error for each star derived from the residuals upon that star alone. It has been the author's experience that a probable error derived from much less than twenty-five residuals is almost without meaning.

In order to gather an idea of the manner in which this probable error was distributed in the several parts of the work, we may proceed as follows: The velocity is computed for each line by the equation

$$v^{\lambda}=k[m_{\text{sun}}-(m_{\text{star}}+\Delta m)] \ .$$

TABLE V

COLLECTED RESULTS

δ Andromedae

$\alpha = 0^h\ 34^m.0$ $\delta = +30°\ 19'$

Plate No.	Date of Photograph	Observed Velocity V. L.	Observed Velocity V. R.	Observed Velocity Mean	Red. to ☉	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
909....	Oct. 15, 1904	+3.9	−0.1	+1.9	−1.2	+0.7	11	12	Maag
913....	" 17, "	−1.4	−2.6	−2.0	−2.2	−4.2	13	13	"
914....	" 18, "	+1.5	±0.0	+0.8	−2.6	−1.8	17	17	"
916....	" 21, "	+1.5	+0.6	+1.0	−4.1	−3.1	15	15	"
917....	" 24, "	+4.4	+2.4	+3.4	−5.4	−2.0	17	17	"

Mean of Velocities = −2.1

α Cassiopeiae[1]

$\alpha = 0^h\ 34^m.8$ $\delta = +56°\ 0'$

Plate No.	Date of Photograph	V. L.	V. R.	Mean	Red. to ☉	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
534....	Nov. 2, 1898	± 0.0	− 4.0	− 2.0	− 2.0	− 4.0	11	12	Lord
535....	" 7, "	± 0.0	+ 2.7	+ 1.4	− 3.7	− 2.3	11	12	"
536....	" 11, "	+11.4	+10.1	+10.8	− 5.1	+ 5.7	10	10	"
539....	" 20, "	+ 8.7	+ 3.2	+ 6.0	− 8.1	− 2.1	11	10	"
540....	Dec. 8, "	+14.0	+14.4	+14.2	−13.6	+ 0.6	11	11	"

Mean of Velocities = −0.4

Plate No.	Date of Photograph	V. L.	V. R.	Mean	Red. to ☉	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
801....	Sept. 24, 1903	− 9.9	−11.5	−10.7	+11.4	+ 0.7	13	13	Maag
806....	Oct. 12, "	− 9.9	− 8.9	− 9.4	+ 5.9	− 3.5	14	14	"
809....	" 18, "	− 5.9	− 7.3	− 6.6	+ 3.9	− 2.7	15	15	"
813....	" 24, "	− 3.4	− 6.0	− 4.7	+ 1.8	− 2.9	17	16	"
815....	" 25, "	− 5.9	− 5.7	− 5.8	+ 1.4	− 4.4	17	17	"

Mean of Velocities = −2.6

η Cassiopeiae

$\alpha = 0^h\ 43^m.0$ $\delta = +57°\ 17'$

Plate No.	Date of Photograph	V. L.	V. R.	Mean	Red. to ☉	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
925....	Oct. 30, 1904	+ 9.4	+ 6.2	+ 7.8	+ 0.4	+ 8.2	15	15	Maag
930....	" 31, "	+10.1	+ 8.8	+ 9.4	+ 0.1	+ 9.3	18	18	"
936....	Nov. 6, "	+12.0	+ 9.9	+11.0	− 2.1	+ 8.9	19	19	"
941....	" 11, "	+13.0	+12.1	+12.6	− 3.9	+ 8.7	15	15	"
945....	" 22, "	+16.2	+16.8	+16.5	− 7.7	+ 8.8	19	19	"

Mean of Velocities = +8.8

η Piscium[2]

$\alpha = 1^h\ 26^m.2$ $\delta = +14°\ 50'$

Plate No.	Date of Photograph	V. L.	V. R.	Mean	Red. to ☉	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
948....	Nov. 30, 1904	+34.3	+33.1	+33.7	−20.6	+13.1	17	17	Maag
953....	Dec. 30, "	+47.2	+43.7	+45.4	−28.9	+16 5	17	17	"
956....	" 31, "	+47.2	+44.7	+46.0	−29.0	+17.0	15	15	"
960....	Jan. 1, 1905	+49.5	+48.0	+48.8	−29.1	+19.7	13	13	"

Mean of Velocities = +16.6

[1]Earlier measures: Vogel, 1890, −14.9; Scheiner, 1890, −15.6; Campbell, 1896, −4.3; Lord, 1897, −0.6. The first series, taken with two 60° dense-flint prisms. Spectroscope covered with felt and velvet bag. Comparison $H\gamma$ only. Measured by placing plate film to film with solar standard.

[2] Suspected variable.

TABLE V—*Continued*

γ Andromedae

$\alpha = 1^h\ 57^m.8$ $\delta = +41°\ 51'$

Plate No.	Date of Photograph	Observed Velocity V. L.	Observed Velocity V. R.	Observed Velocity Mean	Red. to ⊙	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
910....	Oct. 15, 1904	−11.5	−13.3	−12.4	+ 8.8	− 3.6	17	17	Maag
920....	" 29, "	− 9.4	−12.5	−11.0	+ 2.7	− 8.3	13	13	"
926....	" 30, "	− 9.9	−10.3	−10.1	+ 2.3	− 7.8	17	17	"
931....	" 31, "	−10.3	− 7.0	− 8.6	+ 1.8	− 6.8	15	15	"
939 ...	Nov. 6, "	− 7.7	− 8.0	− 7.8	− 1.1	− 8.9	17	17	"

Mean of Velocities = −7.1

α Arietis

$\alpha = 2^h\ 01^m.5$ $\delta = +23°\ 0'$

807....	Oct. 12, 1903	−20.1	−20.2	−20.2	+ 8.5	−11.7	19	19	Maag
814....	" 24, "	−13.9	−14.3	−14.1	+ 2.5	−11.6	18	18	"
816....	" 25, "	−13.6	−13.9	−13.8	+ 2.0	−11.8	17	17	"
819....	" 26, "	−15.4	−14.7	−15.0	+ 1.6	−13.4	19	19	"
820....	" 28, "	−12.1	−15.7	−13.9	+ 0.6	−13.3	16	16	"

Mean of Velocities = −12.4

γ Persei

$\alpha = 2^h\ 57^m.6$ $\delta = +53°\ 7'$

927....	Oct. 30, 1904	− 0.1	− 0.3	− 0.2	+ 8.8	+ 8.6	17	17	Maag
932....	" 31, "	− 1.9	− 3.7	− 2.8	+ 8.4	+ 5.6	17	17	"
938....	Nov 6, "	+ 0.7	− 1.2	− 0.2	+ 6.0	+ 5.8	16	15	"
942....	" 11, "	− 0.7	± 0.0	− 0.4	+ 4.0	+ 3.6	16	16	"
946....	" 22, "	+ 3.4	+ 2.3	+ 2.8	− 1.0	+ 1.8	17	17	"

Mean of Velocities = +5.1

α Persei

$\alpha = 3^h\ 17^m.2$ $\delta = +49°\ 31'$

922.	Oct. 29, 1904	− 9.2	− 9.5	− 9.4	+10.4	+ 1.0	14	14	Maag
928....	" 30, "	− 9.4	− 8.6	− 9.0	+10.0	+ 1.0	14	14	"
940....	Nov. 6, "	− 6.4	− 5.6	− 6.0	+ 7.0	+ 1.0	16	16	"
943.. .	" 11, "	− 6.9	− 6.5	− 6.7	+ 4.9	− 1.8	16	16	"
947....	" 22, "	+ 3.3	+ 0.8	+ 2.0	− 0.1	+ 1.9	15	15	"

Mean of Velocities = +0.6

α Tauri

$\alpha = 4^h\ 30^m.2$ $\delta = +16°\ 18'$

949....	Nov. 30, 1904	+58.3	+59.1	+58.7	− 0.1	+58.6	19	19	Maag
951....	Dec. 14, "	+60.6	+61.4	+61.0	− 7.3	+53.7	19	19	"
954....	" 30, "	+70.4	+68.4	+69.4	−15.1	+54.3	16	16	"
957....	" 31, "	+71.4	+70.7	+71.0	−15.5	+55.5	16	16	"
961....	Jan. 1, 1905	+73.1	+73.5	+73.3	−15.9	+57.4	18	18	"

Mean of Velocities = +55.9

TABLE V—*Continued*

$\alpha = 5^h\ 9^m.3$ *α Aurigae* $\delta = +45°\ 54'$

Plate No.	Date of Photograph	Observed Velocity			Red. to ⊙	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
		V. L.	V. R.	Mean					
562....	Jan. 22, 1899	+57.1	+55.7	+56.4	−18.7	+37.7	15	16	Lord
563....	" 25, "	+56.1	+53.6	+54.8	−19.8	+35.0	19	22	"
564....	" 29, "	+51.9	+47.5	+49.7	−21.1	+28.6	19	20	"

Mean of Velocities = +33.8

$\alpha = 7^h\ 38^m.4$ *κ Geminorum*[1] $\delta = +24°\ 38'$

595....	Jan. 21, 1900	+27.1	+25.9	+26.5	− 4.9	+21.6	15	15	Lord
601....	" 26, "	+28.9	+27.0	+28.0	− 7.2	+20.8	15	15	"
602....	" 28, "	+33.4	+30.2	+31.8	− 8.4	+23.4	14	14	"
603....	Feb. 13, "	+40.8	+36.1	+38.4	−15.8	+22.6	15	15	"
605....	" 19, "	+40.2	+36.8	+38.5	−18.4	+20.1	15	15	"

Mean of Velocities = +21.7

$\alpha = 7^h\ 39^m.2$ *β Geminorum* $\delta = +28°\ 16'$

848....	Mar. 23, 1904	+31.4	+32.3	+31.8	−27.6	+ 4.2	15	15	Maag
852....	" 28, "	+32.6	+29.8	+31.2	−28.3	+ 2.9	17	16	"
857....	April 4, "	+35.0	+33.7	+34.4	−29.0	+ 5.4	21	21	"
858....	" 5, "	+38.3	+36.4	+37.4	−29.1	+ 8.3	17	17	"
860....	" 14, "	+34.3	+35.1	+34.7	−29.2	+ 5.5	16	16	"

Mean of Velocities = +5.3

$\alpha = 8^h\ 22^m.0$ *o Ursae Majoris*[2] $\delta = +61°\ 3'$

604....	Feb. 13, 1900	+36.1	+32.0	+34.0	−12.4	+21.6	17	17	Lord
606....	" 19, "	+36.9	+35.0	+36.0	−14.3	+21.7	17	17	"
611....	Mar. 21, "	+44.2	+40.5	+42.4	−21.1	+21.3	15	16	"
613....	" 22, "	+46.5	+43.3	+44.9	−21.2	+22.7	14	16	"
615....	" 31, "	+43.3	+39.5	+41.4	−22.5	+18.9	16	15	"
617....	Apr. 4, "	+46.1	+43.3	+44.7	−22.7	+22.0	14	16	"

Mean of Velocities = +21.4

$\alpha = 10^h\ 14^m.4$ *γ Leonis* $\delta = +20°\ 21'$

861....	Apr. 14, 1904	− 3.7	− 7.6	− 5.6	−23.9	−29.5	16	16	Maag
862....	" 16, "	− 6.2	− 9.4	− 7.8	−24.5	−32.3	11	11	"
864....	" 19, "	− 6.0	−12.9	− 9.4	−25.2	−34.6	17	17	"
868....	May 5, "	− 2.5	− 6.3	− 4.4	−28.1	−32.5	16	16	"
870....	" 9, "	− 3.5	− 5.2	− 4.4	−28.4	−32.8	15	15	"

Mean of Velocities = −32.3

[1] All spectrograms taken with two dense 60° prisms. Comparison *Fe* and *Hγ*. Reduction slightly different from that explained in paper.

[2] Spectrograms taken and reduced same as *κ Geminorum*.

TABLE V—*Continued*

$\alpha = 10^h\ 57^m\!.6$ *α Ursae Majoris* $\delta = +62°\ 17'$

Plate No.	Date of Photograph	Observed Velocity V. L.	Observed Velocity V. R.	Observed Velocity Mean	Red. to ⊙	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
681....	Apr. 20, 1902	+15.9	+11.0	+13.4	−18.5	− 5.1	17	17	Lord
682....	" 22, "	+14.3	+ 9.6	+12.0	−18.6	− 6.6	19	19	"
683....	" 23, "	+15.8	+12.8	+14.3	−18.7	− 4.4	16	18	"
687....	" 24, "	+15.3	+11.6	+13.4	−18.7	− 5.3	19	19	"
690....	" 27, "	+14.8	+11.3	+13.0	−18.9	− 5.9	16	16	"

Mean of Velocities = −5.5

$\alpha = 11^h\ 45^m\!.5$ *β Virginis* $\delta = +2°\ 20'$

Plate No.	Date of Photograph	V. L.	V. R.	Mean	Red. to ⊙	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
696....	Apr. 30, 1902	+28.4	+27.0	+27.7	−20.3	+ 7.4	19	19	Lord
706....	May 8, "	+33.0	+28.2	+30.6	−23.0	+ 7.6	18	18	"
709....	" 9, "	+30.9	+29.8	+30.4	−23.2	+ 7.2	16	16	"
716....	" 26, "	+37.8	+35.3	+36.6	−27.3	+ 9.3	19	19	"
717....	" 28, "	+39.0	+34.8	+36.9	−27.7	+ 9.2	21	21	"

Mean of Velocities = +8.1

Plate No.	Date of Photograph	V. L.	V. R.	Mean	Red. to ⊙	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
696....	Duplicate Measures	+28.6	+28.8	+28.7		+ 8.4	18	18	Maag
706....		+30.5	+29.6	+30.0		+ 7.0	16	15	"
709....		+31.8	+32.0	+31.9		+ 8.7	18	18	"
716....		+35.4	+34.0	+34.7		+ 7.4	19	19	"
717....		+36.3	+37.7	+37.0		+ 9.3	18	18	"

Mean of Velocities = +8.2

$\alpha = 12^h\ 7^m\!.52$ *ε Virginis* $\delta = +11°\ 30'$

Plate No.	Date of Photograph	V. L.	V. R.	Mean	Red. to ⊙	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
713....	May 12, 1902	+ 7.6	+ 9.2	+ 8.4	−19.0	−10.6	17	17	Maag
719....	June 9, "	+15.4	+14.8	+15.1	−26.2	−11.1	15	15	"
722....	" 11, "	+19.0	+19.4	+19.2	−26.4	− 7.2	14	14	"
723....	" 16, "	+15.6	+14.1	+14.8	−26.9	−12.1	19	19	"
725....	" 21, "	+16.5	+16.4	+16.4	−27.4	−11.0	17	17	"

Mean of Velocities = −10.4

$\alpha = 13^h\ 49^m\!.9$ *η Boötis*[1] $\delta = +18°\ 54'$

Plate No.	Date of Photograph	V. L.	V. R.	Mean	Red. to ⊙	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
572....	May 13, 1899	+30.0	+24.2	+27.1	−14.6	+12.5	11	10	Lord
581....	" 24, "	+33.9	+29.2	+31.6	−18.2	+13.4	18	17	"
585....	June 2, "	+34.3	+33.9	+34.1	−20.4	+13.7	11	10	"
586....	" 10, "	+41.1	+35.4	+38.2	−22.6	+15.6	13	11	"
587....	" 17, "	+40.6	+33.3	+37.0	−23.9	+13.1	13	12	"
588....	" 18, "	+35.8	+34.4	+35.1	−24.0	+11.1	10	13	"
591....	" 29, "	+40.0	+36.5	+38.2	−25.3	+12.9	13	13	"

Mean of Velocities = +13.2

[1] Variable discovered by Dr. Moore. *Lick Observatory Bulletin* No. 70; *Astrophysical Journal*, **19**, 246, 1904. See *η Boötis* on next page.

TABLE V—*Continued*

η Boötis

$\alpha = 13^h\ 49^m.9$ $\delta = +18°\ 54'$

Plate No.	Date of Photograph	Observed Velocity V. L.	Observed Velocity V. R.	Observed Velocity Mean	Red. to ☉	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
685....	Apr. 23, 1902	+13.2	+11.7	+12.4	− 6.3	+ 6.1	16	16	Maag
692....	" 27, "	+18.0	+18.1	+18.0	− 7.9	+10.1	17	17	"
699....	May 2, "	+20.5	+19.5	+20.0	−10.0	+10.0	14	14	"
707....	" 8, "	+18.9	+16.6	+17.8	−12.4	+ 5.4	11	11	"
710....	" 9, "	+20.2	+15.6	+17.9	−12.8	+ 5.1	12	12	"

Mean of Velocities = +7.3

α Boötis[1]

$\alpha = 14^h\ 11^m.1$ $\delta = +19°\ 42'$

Plate No.	Date of Photograph	V. L.	V. R.	Mean	Red. to ☉	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
686....	Apr. 23, 1902	+ 2.2	+ 0.3	+ 1.2	− 4.1	− 2.9	19	14	Maag
700....	May 2, "	+ 5.2	+ 3.7	+ 4.4	− 7.9	− 3.5	15	15	"
711....	" 9, "	+ 6.7	+ 6.8	+ 6.8	−10.7	− 3.9	13	13	"
{ 714...	" 12, "	+12.9	+11.6	+12.2	−11.8	+ 0.4	} 16	16	"
{ 714...	Duplicate	+12.4	+11.6	+12.0	−11.8	+ 0.2	} 16	16	"
720....	June 9, "	+17.7	+17.2	+17.4	−21.2	− 3.8	15	15	"
726....	" 21, "	+21.6	+19.0	+20.3	−23.7	− 3.4	21	21	"
871....	May 10, 1904	+ 8.4	+ 8.6	+ 8.5	−11.0	− 2.5	17	17	"
881....	" 28, "	+11.0	+12.2	+11.6	−17.3	− 5.7	18	18	"

Mean of Velocities = −3.2

ε Boötis

$\alpha = 14^h\ 40^m.6$ $\delta = +27°\ 30'$

Plate No.	Date of Photograph	V. L.	V. R.	Mean	Red. to ☉	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
872....	May 10, 1904	− 7.7	− 8.7	− 8.2	− 8.5	−16.7	19	19	Maag
876....	" 20, "	− 4.1	− 7.0	− 5.6	−11.9	−17.5	15	15	"
877....	" 27, "	+ 1.4	+ 1.1	+ 1.2	−14.0	−12.8	17	17	"
882....	" 28, "	− 0.5	− 3.7	− 2.1	−14.3	−16.4	16	16	"
885....	June 3, "	+ 2.9	+ 0.5	+ 1.7	−15.9	−14.2	14	14	"

Mean of Velocities = −15.5

α Serpentis

$\alpha = 15^h\ 39^m.3$ $\delta = +6°\ 44'$

Plate No.	Date of Photograph	V. L.	V. R.	Mean	Red. to ☉	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
878....	May 27, 1904	+11.8	+11.7	+11.8	− 6.8	+ 5.0	15	15	Maag
889....	June 11, "	+15.8	+16.7	+16.2	−13.0	+ 3.2	13	13	"
892....	" 12, "	+23.2	+20.4	+21.8	−13.4	+ 8.4	11	11	"
895....	" 16, "	+23.6	+20.5	+22.0	−15.0	+ 7.0	16	16	"
897....	" 17, "	+21.7	+21.0	+21.4	−15.4	+ 6.0	14	14	"

Mean of Velocities = +5.9

[1] Plate 714 rejected before measuring as being too poor to measure. Then later measured and reduced under a misunderstanding. Should be rejected.

TABLE V—*Continued*

ζ Herculis

$\alpha = 16^h\ 37^m.5$ $\delta = +31° 47'$

Plate No.	Date of Photograph	Observed Velocity			Red. to ⊙	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
		V. L.	V. R.	Mean					
879....	May 27, 1904	−66.4	−67.2	−66.8	− 1.7	−68.5	18	18	Maag
884....	“ 28, “	−67.4	−67.6	67.5	− 2.0	−69.5	17	17	“
887....	June 9, “	−67.5	−66.4	67.0	− 5.5	−72.5	14	14	“
896....	“ 16, “	−64.9	−67.1	66.0	− 7.1	−73.1	18	18	“
898....	“ 17, “	−60.1	−59.7	59.9	− 7.4	−67.3	14	14	“

Mean of Velocities = −70.2

β Draconis

$\alpha = 17^h\ 28^m2$ $\delta = +52° 23'$

754....	July 22, 1903	−15.7	−14.4	−15.0	− 5.0	−20.0	16	16	Maag
758....	“ 24, “	−10.5	−11.4	−11.0	− 5.6	−16.6	15	15	“
761....	“ 31, “	−12.0	−12.4	−12.2	− 6.4	−18.6	16	16	“
764....	Aug. 7, “	− 8.6	− 9.5	− 9.0	− 6.9	−15.9	17	17	“
766....	“ 9, “	− 9.1	−10.1	− 9.6	− 6.8	−16.4	15	15	“

Mean of Velocities = −17.5

χ Draconis

$\alpha = 18^h\ 22^m.9$ $\delta = +72° 41'$

787....	Sept. 1 1903	+26.9	+26.9	+26.9	+ 3.2	+30.1	12	12	Maag
790....	“ 2, “	+29.7	+29.2	+29.4	+ 3.2	+32.6	12	12	“

Mean of Velocities = +31.4

δ Draconis

$\alpha = 19^h\ 12^m.5$ $\delta = +67° 29'$

756....	July 23, 1903	+25.9	+24.6	+25.2	+ 3.5	+28.7	17	17	Maag
765....	Aug. 7, “	+26.6	+26.1	+26.4	+ 3.2	+29.6	19	19	“
768....	“ 11, “	+24.2	+23.6	+23.9	+ 2.9	+26.8	19	19	“
771....	“ 16, “	+24.5	+22.6	+23.6	+ 2.8	+26.4	16	16	“
774....	“ 17, “	+24.7	+21.9	+23.3	+ 2.9	+26.2	14	14	“

Mean of Velocities = +27.5

β Cygni

$\alpha = 19^h\ 26^m.7$ $\delta = +27° 45'$

903....	Sept. 10, 1904	− 9.3	−13.7	−11.5	−14.5	−26.0	14	14	Maag
904....	“ 13, “	− 6.9	− 6.8	− 6.8	−15.2	−22.0	13	13	“
905....	“ 14, “	− 4.9	− 6.4	− 5.6	−15.4	−21.0	15	15	“
906....	“ 15, “	− 5.1	− 4.9	− 5.0	−15.6	−20.6	20	20	“
907....	“ 17, “	− 7.1	− 7.4	− 7.2	−15.9	−23.1	13	13	“

Mean of Velocities = −22.5

TABLE V—*Continued*

γ Cygni

$\alpha = 20^h\ 18^m6$ $\delta = +39°\ 56'$

Plate No.	Date of Photograph	Observed Velocity V. L.	Observed Velocity V. R.	Observed Velocity Mean	Red. to ☉	Radial Velocity	No. of Lines, V. L.	No. of Lines, V. R.	Measured by
782....	Aug. 21, 1903	− 2.1	− 2.8	− 2.4	− 1.4	− 3.8	16	16	Maag
785....	" 23, "	− 1.6	− 2.5	− 2.0	− 1.9	− 3.9	14	14	"
788....	Sept. 1, "	+ 0.2	± 0.0	+ 0.1	− 4.5	− 4.4	17	17	"
792....	" 6, "	− 0.6	+ 1.9	+ 0.6	− 5.8	− 5.2	13	13	"
794....	" 12, "	+ 4.0	+ 4.2	+ 4.1	− 7.2	− 3.1	19	19	"

Mean of Velocities = −4.1

ε Cygni

$\alpha = 20^h\ 42^m2$ $\delta = +33°\ 36'$

770....	Aug. 12, 1903	−16.2	−16.1	−16.2	+ 2.1	−14.1	17	16	Maag
772....	" 16, "	−12.8	−14.0	−13.4	+ 1.1	−12.3	13	13	"
775....	" 17, "	−11.9	−12.5	−12.2	+ 0.5	−11.7	15	15	"
780....	" 20, "	−16.8	−13.9	−15.4	− 0.2	−15.6	18	18	"
783....	" 21, "	−10.9	−10.6	−10.8	− 0.4	−11.2	18	18	"

Mean of Velocities = −13.0

ε Pegasi

$\alpha = 21^h\ 39^m3$ $\delta = +9°\ 25'$

799....	Sept. 24, 1903	+24.1	+23.4	+23.8	−14.3	+ 9.5	13	13	Maag
802....	" 25, "	+22.4	+22.8	+22.6	−14.6	+ 8.0	13	12	"
808....	Oct. 18, "	+27.2	+26.1	+26.6	−22.8	+ 3.8	17	17	"
811....	" 19, "	+27.3	+26.4	+26.8	−23.1	+ 3.7	16	16	"
812....	" 24, "	+29.9	+29.2	+29.6	−24.2	+ 5.4	13	13	"

Mean of Velocities = +6.1

δ Cephei[1]

$\alpha = 22^h\ 25^m5$ $\delta = +57°\ 54'$

800....	Sept. 24, 1903	−27.0	−28.6	−27.8	+ 3.7	−24.1	10	10	Maag
803....	" 25, "	−10.4	−12.1	−11.2	+ 3.5	− 7.7	19	20	"

η Pegasi

$\alpha = 22^h\ 38^m3$ $\delta = +29°\ 42'$

776....	Aug. 17, 1903	−11.2	−13.0	−12.1	+11.9	− 0.2	17	17	Maag
781....	" 20, "	−10.5	−11.2	−10.8	+10.8	± 0.0	18	18	"
784....	" 21, "	−13.5	−13.0	−13.2	+10.6	− 2.6	17	17	"
789....	Sept. 1, "	− 8.0	− 8.4	− 8.2	+ 6.3	− 1.9	17	17	"
793....	" 6, "	− 6.9	− 9.0	− 8.0	+ 4.4	− 3.6	17	17	"

Mean of Velocities = −1.7

[1] Variable radial velocity discovered by Bélopolsky in 1898. Rediscovered here.

Here m_{sun}, m_{star}, and Δm are respectively the values of m for the given line given in the table of solar lines, the mean of the three settings on the star line, and the correction computed by the curve

$$\Delta m = x + by + cz \cdot .$$

k is the constant to convert displacements into velocity. We have therefore

$$r_v = k\sqrt{(r_{\text{sun}})^2 + (r_{\text{star}})^2 + (r_{\Delta m})^2} \ .$$

To evaluate these several probable errors, Mr. Maag selected three plates—good, fair, and poor. On each plate he selected five representative lines and made twenty-five pointings on each. For each line he computed the probable error of a single pointing, the average of the fifteen being 0.68, the values lying between the limits 0.34 and 0.81 in thousandths of a millimeter. As each line was bisected three times, we may assume that $r_{\text{star}} = \pm 0.5$ km per sec. The solar lines were much sharper and were measured on two different days, but each line depended upon the difference of two sets of pointings. We shall therefore be safe if we assume $r_{\text{sun}} = \pm 0.5$ km per sec. The value of $r_{\Delta m}$ was computed from the residuals between the observed C.–O. and the computed C.–O. for the comparison lines for ten plates, using the measures, violet end left. The ten values range from 0.81 to 2.11 with a mean of 1.3. From this we find $r_v = 1.85$ km per sec., using $k = 1.25$, its value for the middle of the plate. On the average, there were from 15 to 17 lines measured on each plate, and each plate was measured in two positions, whence we find 0.3 km per sec. as the probable error of a single plate deduced in this way as against 1.88 by the first method. This difference can only be due to two causes, namely, the error of identification of the lines and what might be called the probable error of taking the photograph. The first of these is very hard to determine, and as an attempted solution I selected ten stars at random and derived the probable errors of a single line from their mean for that plate alone, using the measures violet end left. These range from 1.8 to 4.8, with a mean of about 3.0 km per sec. This gives ± 0.5 km per sec. as the probable error of a single plate. The difference between this value and ± 0.3 is due, I believe, to errors in identification. This is smaller than we should expect, which may be par-

Venus

Plate No.	Date of Photograph	Observed Velocity			Computed Velocity	C.–O.	Number of Lines		Measured by
		V. L.	V. R.	Mean			V. L.	V. R.	
651....	Nov. 27, 1901	− 9.8	−12.1	−11.0	−13.2	−2.2	21	22	Lord
660....	Dec. 4, "	− 9.7	−10.8	−10.2	−13.2	−3.0	17	19	"
661....	" 15, "	−10.9	−13.1	−12.0	−13.1	−1.1	20	20	"
666....	" 30, "	−10.2	−10.2	−10.2	−12.4	−2.2	18	17	"
668....	" 31, "	− 9.7	−10.7	−10.2	−12.3	−2.1	17	18	"
673....	Jan. 1, 1902	−10.9	−13.5	−12.2	−12.0	+0.2	20	20	"
676....	" 6, "	− 8.0	− 9.8	− 8.9	−11.9	−3.0	19	19	"
689....	Apr. 26, 1902	+15.5	+12.6	+14.0	+14.0	±0.0	20	21	Lord
695....	" 29, "	+19.4	+16.6	+18.0	+14.0	−4.0	21	21	"
705....	May 5, "	+18.4	+14.4	+16.4	+13.9	−2.5	14	13	"
651....	Duplicate	−10.9	−10.3	−10.6	−13.2	−2.6	20	20	Maag
658....	Nov. 30, 1901	−10.6	−10.8	−10.7	−13.3	−2.6	15	15	"
660....	Duplicate	− 8.4	− 8.8	− 8.6	−13.2	−4.6	20	20	"
661....	"	− 9.8	− 8.1	− 9.0	−13.1	−4.1	20	20	"
666....	"	− 9.0	− 8.2	− 8.6	−12.4	−3.8	19	19	"
676....	"	− 7.1	− 6.8	− 7.0	−11.8	−4.8	13	13	"
689....	Duplicate	+13.8	+15.0	+14.4	+14.0	−0.4	13	13	Maag
705....	"	+17.3	+16.4	+16.8	+13.9	−2.9	17	17	"
731....	Apr. 10, 1903	− 7.6	− 8.2	− 7.9	− 9.8	−1.9	18	18	Maag
734....	" 18, "	− 9.3	−11.9	−10.6	−10.4	+0.2	12	12	Lord
747....	July 5, "	−18.2	−18.0	−18.1	−13.9	+4.2	18	18	Maag
748....	" 6, "	−15.4	−17.1	−16.2	−13.8	+2.4	18	17	"
749....	" 7, "	−12.2	−14.2	−13.2	−13.9	−0.7	15	15	"
751....	" 8, "	−16.7	−17.6	−17.2	−13.9	+3.3	19	19	"
952....	Dec. 30, 1904	−11.2	−11.3	−11.2	−11.7	−0.5	18	18	Maag
955....	" 31, "	−12.4	−10.7	−11.6	−11.9	−0.3	15	15	"
962....	Jan. 16, 1905	−10.5	− 9.7	−10.1	−12.5	−2.4	18	18	"
964....	" 26, "	−11.1	−12.5	−11.8	−12.7	−0.9	20	20	"
965....	Feb. 4, "	−10.4	− 8.9	− 9.6	−13.0	−3.4	17	17	"
966....	" 7, "	−11.2	−14.8	−13.0	−13.0	±0.0	16	16	"
967....	" 10, "	−11.3	−13.0	−12.2	−13.1	−0.9	18	18	"
968....	" 15, "	−12.7	−12.2	−12.4	−13.1	−0.7	16	16	"

tially explained by the close similarity between the spectra of most of the stars I have observed and that of the Sun. The balance, namely, $\sqrt{(1.88)^2-(0.5)^2}=1.80$, is, I believe, entirely due to the numerous sources of error in taking the photograph. It forms practically the entire source of error, and I believe it could be materi-

ally reduced with a modernized, constant-temperature, rigid form of mounting for the spectroscope.

The final test is of course the observed velocities of the planets. I give above the observations of *Venus* in the line of sight. The velocity of *Venus* was computed in accordance with Campbell's paper previously cited. It is to be noted that there is a persistent constancy in the sign of the residuals C.–O. I am utterly at a loss to account for it, and can explain it only by the much abused "personal equation." It is very small, only about 0.002 on the plate, and could, I believe, be applied as a constant correction to my velocities.

In conclusion I wish to express my indebtedness to my assistant, Mr. Maag, who has done nearly all the computation and measurement. The photographs were always taken by myself. I should like also to call attention to the fact that it has been possible, with this small dispersion, to secure measurable spectrograms of stars of the fifth photographic magnitude, with a telescope of only 12½ inches clear aperture, and that in a bad sky. I feel confident that a spectroscope built from the ground up for this purpose would materially reduce the errors. Now, if such an instrument could be attached to a three-foot reflector, I believe we could easily reach stars of the photographic magnitude seven and one-half. It would, however, be restricted as to type of spectra.

Emerson McMillin Observatory,
Columbus, Ohio,
March 7, 1905.

THE MOTION OF THE MATTER COMPOSING THE TAIL OF COMET 1903 IV, OBSERVED JULY 24, 1903

By R. JAEGERMANN

Professor E. E. Barnard[1] observed first a motion of the tail on three photographs of the comet 1903 IV, taken July 24, 1903; and both Mr. Sebastian Albrecht[2] and Mr. Roberts[3] have obtained the same results by photographic means. Professor H. Kreutz[4] has investigated carefully the photographs secured by Mr. Roberts. I learn from the Greenwich Observatory[5] that on the photograph obtained there on July 24 there is, on account of the large scale, no trace of that side of the piece separated from the tail which is nearer the nucleus. This piece lies on the forward side of the comet with reference to the direction of motion of the comet. Therefore there is left for comparison only the photograph taken by Mr. Smith[6] at the Yale Observatory. Owing to the fact that the time of exposure of this photograph cannot be ascertained, it must be omitted from the discussion.

The middle of the time of exposure has been considered as the epoch for the photographs of Roberts and Quénisset. For the photographs of Barnard, Curtiss, and Wallace we have adopted the beginning of the exposure increased by 30 minutes; this was done on account of the long duration of these exposures.

By a triangulation by means of neighboring comparison stars, the co-ordinates α, δ of the particular end of the tail were divided on the plates of Roberts,[7] Quénisset, and the reprints of the photographs of Barnard, Curtiss, and Wallace as given in the *Astrophysical Journal* and the *Bulletin of the Lick Observatory*. The positions of the stars were taken from the catalogues of the *Astronomische Gesell-*

[1] *Astrophysical Journal*, **18**, 212, 1903.

[2] *Lick Observatory Bulletin* No. 52; *Astrophysical Journal*, **19**, 124, 1904.

[3] *Knowledge*, 26, 201, 1903.

[4] *A. N.*, **166**, 279, 1904.

[5] *Monthly Notices*, 64, 85, December 1903.

[6] *Popular Astronomy*, **11**, 519.

[7] I. Roberts' photograph was kindly furnished to the writer by Mrs. Dorothea Klumpke Roberts.

schaft. The co-ordinates α_{comet}, δ_{comet} of the nucleus have been computed from Perrine's[1] parabolic elements, and corrections to them have been applied from the observations of the comet as published in *Astronomische Nachrichten* and the *Bulletin of the Lick Observatory.* By means of the *Berliner Jahrbuch* we have computed the $\alpha\odot$ and $\delta\odot$ which belong to the epoch. These are the results:

Observatory	Observer	Time of Exposure	Epoch (G. M. T.)	α (1903.0)	δ
Crowborough...	Roberts....	0h 45m	1903 July 24.43821	205° 56′ 15″	+64° 42′ 44″
Nanterre.......	Quénisset..	1 0	24.47917	206 2 0	64 38 18
Yerkes.........	Barnard...	2 37	24.64375	206 36 5	64 22 43
Lick...........	Curtiss....	5 30	24.72917	206 59 41	64 13 56
Yerkes.........	Wallace....	2 30	24.77014	207 11 35	64 9 7

For the sake of completeness we have given the seconds of arc, although they must be considered quite uncertain. Indeed, it is quite difficult to identify on comet plates corresponding points and to give the correct epochs of observations.

The co-ordinates of the Sun and the comet, the distance (ρ) of the nucleus from the Earth, and finally the angular distance s of the end of the tail (α, δ) from the nucleus (α_{comet}, δ_{comet}) are given in the following table:

	$\alpha\odot$	$\delta\odot$	α Comet	δ Comet	Log ρ	s
R............	123° 1′ 49.″7	+19° 59′10.″9	202° 21′ 28″	+64° 34′ 56″	9.554282–10	1° 32′ 17″
Q............	4 16.1	58 40.3	202 5 12	30 30	9.555200	1 41 57
B............	14 4.0	56 37.1	201 1 15	12 36	9.558893	2 25 32
C............	19 9.0	55 32.9	200 28 59	3 16	9.560812	2 50 39
W...........	21 35.3	55 2.1	200 13 45	63 58 46	9.561733–10	3 2 56

The second and third values of s are slightly larger than those given by Mr. Albrecht, while the last two show agreement with those derived by Albrecht. These new values of s vary more regularly per hour in the various intervals than those given by Albrecht, as may be seen from the following figures:

	Interval of Time	δs in 1h		Interval of Time	δs in 1h
R.–Q........	0h 59m	0° 9.′9	Q.–C.......	6h 0m	11.′4
R.–B........	4 56	10.8	Q.–W.	6 59	11.6
R.–C........	6 59	11.2	B.–C.......	2 3	12.2
R.–W.......	7 58	11.3	B.–W......	3 2	12.3
Q.–B........	3 57	11.0	C.–W......	0 59	12.5

[1] *Lick Observatory Bulletin* No. 47, 127.

This regular change in the above derived values of s gives a certain justification to their existence. The same results are obtained on adopting the instant of beginning the exposure, as proposed by Albrecht. Bessel's auxiliary angles[1] P, S (P' need not be computed at all), as well as the position angle at the comet's nucleus (p) of the end of the tail, and p_0 of the prolonged radius vector, together with the auxiliary angles $u-P'$, u_0-P' are:[2]

	P	S	p	p_0	$u-P'$	u_0-P'
R..........	178° 37′ 33″	110° 54′ 57″	83° 31′ 58″	89° 20′ 57″	255° 58′ 57″	272° 1′ 31″
Q..........	178 20 8	110 59 12	50 10	89 5 36	257 36 28	6 53
B..........	177 11 32	111 16 0	30 26	88 5 19	259 55 53	28 14
C..........	176 36 48	111 24 34	29 40	87 34 56	261 30 35	39 7
W..........	176 20 23	111 28 39	83 37 47	87 20 35	262 38 0	272 44 18

The angle T gives the perspective reduction, Δ stands for the distance between the end of the tail and nucleus measured in the plane of the comet, $\phi=u-u_0=(u-P')-(u_0-P')$ is the angle between Δ and the radius vector, R is the radius vector of the end of the tail, and finally ω is the angle between R and the axis of the orbit of the comet (negative if before the perihelion). Their values are as follows:[3]

	T	Log Δ	$\phi=u-u_0$	Log R	ω
R..................	103° 4′ 37″	7.997362–10	−16° 2′ 34″	9.976842–10	−107° 8′ 6″
Q..................	101 33 30	8.038981	14 30 25	9.976937	107 5 54
B..................	99 22 36	8.194732	12 32 21	9.977564	106 54 30
C..................	97 54 2	8.264147	11 8 32	9.978025	106 49 16
W..................	96 51 9	8.294064–10	−10 6 18	9.978263–10	−106 47 21

The linear distances, Δ and R, of the end of the tail from the nucleus and from the Sun, grow in the same regular fashion that was noticed in s; they do not jump in the way they do in Albrecht's tables.[4] They are, in fact, as follows:

[1] Bessel's formulæ for computing these and other angles were first corrected by Th. Bredichin as early as 1862 in his work *On the Tails of Comets* (Moscow, 1862; in Russian). But they have remained almost unknown on account of the limited use of the language of the original.

[2] See, for instance, *Lick Observatory Bulletin* No. 42, p. 101; and No. 52, p. 167 or the *Astrophysical Journal*, **19**, 125, 1904.

[3] Professor Dr. Th. Bredichin's *Mechanische Untersuchungen über Cometenformen*, in systematischer Darstellung von R. Jaegermann (St. Petersburg, 1903; Voss Sortiment, Leipzig), pp. 305, 314.

[4] *Lick Observatory Bulletin* No. 52, p. 164.

	$\delta\Delta$ in 1 Sec.	δR in 1 Sec.		$\delta\Delta$ in 1 Sec.	δR in 1 Sec.
R.–Q.	42.2 km	8.8 km	Q.–C.	51.4 km	16.5 km
R.–B.	48.1	13.3	Q.–W.	52.0	17.2
R.–C.	50.1	15.4	B.–C.	55.0	20.4
R.–W.	50.8	16.2	B.–W.	55.1	20.9
Q.–B.	49.6	14.4	C.–W.	55.3	22.0

$\delta\Delta$ and δR for the interval $Q.-B.$ really belong in the third and not in the fifth line, and they therefore do not depart from the general regular behavior of the rest. The same holds true for δs for the same interval. By a graphic representation of R and ω, it can easily be seen that that end of the tail which is ahead of the radius when prolonged has moved in $7^h\ 58^m$ over an arc which is convex with respect to the Sun. The length of the arc is 0.00658 astronomical units, from which follows a mean orbital velocity of 34.3 km per second. During this interval of time of $7^h\ 58^m$ the end of the tail moved away from the Sun with a velocity of 16.2 km in the direction of the radius thus prolonged, and it moved away from the nucleus (measured likewise along R) with a mean velocity $\delta\,(\Delta \cos \phi)=51.2$ km. The nucleus approached the Sun during this time with a mean velocity $\delta r=\delta(\Delta\ \cos\ \phi)-\delta R=35.0$ km, while its orbital velocity was 43.5 km.

From this it is evident that the end of the tail has been moving on an arc which is convex toward the Sun, and that proves indisputably that the matter constituting the tail has been under the influence of a repulsive force. The convex arc evidently is part of a hyperbola, convex toward the Sun. The fact that the end of the tail was on all of the five plates constantly far ahead of the prolongation of the radius vector proves, on the basis of the mechanical theory of comets' tails, that the tail-matter emanated with a considerable initial velocity g, i. e., at a negative angle G to the radius vector.

Matter thrown out before the perihelion passage, as in the present case, will, according to the theory, first approach the Sun, then pass through its hyperbolic perihelion, and after that depart from the Sun continuously. The steady increase of R shows that the end of the tail under investigation had passed through the hyperbolic perihelion before Roberts' photograph was taken. In obtaining the elements of the hyperbolic orbit we must satisfy these two conditions:

1. The perihelion distance Q must be smaller, or at most, equal to the value of R. (Roberts).

2. The time of passage through the perihelion must have taken place before, or at most at, the time of Roberts' photograph.

To fulfil these conditions it was necessary to assume for the repulsive force, $1-\mu$, of the Sun a value greater than 60 units[1] (the unit being the gravitational force of the Sun), hence much larger than those which Bredichin has found, namely, 18 and 36. To obtain the proper values for ω it was, moreover, necessary to assume for g (velocity of emanation) a value even larger than the value $g=0.34$, adopted by Bredichin for the comet of 1744 (for the time unit $\frac{1}{k}=58.13244$ mean solar days), or $g=10.1$ km per second. The values adopted are $1-\mu=89$ and $g=0.42=12.5$ km per second. The increase in the value of g by 0.08 is quite reasonable, since the matter in question is five times as light as in the previous case.

The elements of the hyperbola, which is located in the plane of the comet's orbit (already communicated in *A. N.* 3978), have been derived under the following initial conditions: The matter of the end of the tail is thrown out at the moment $M_0=1903$ July 23.36362 G. M. T. with an initial velocity $g=0.42$ and an angle of projection $G=-21°30'$, with respect to the radius vector. It is under the effective and constant force $\mu=-88.05$ (repulsive).

The elements thus derived are:

$\log P=8.019672-10$	$\log A=9.673273-10$
$\log Q=9.976695-10$	$\psi=\ \ 8°\ 28'\ 29''.8$
$\log E=0.004768$	$\omega_\pi=-107\ \ 17\ \ 29.3$
$M_\pi=1903$ July 24.28684 G. M. T.	

(P = semi-parameter, Q = perihelion distance, E = eccentricity, $2A$ = major axis, ψ = asymptotic angle, ω_π = angle between the axis of the hyperbola and that of the orbit of the comet, M_π = time of passage through the hyperbolic perihelion.)

We compute $\log R$ and ω from these elements for the moments of observation and form the difference between computation and

[1] *Bulletin de l'Académie Impériale des Sciences de St. Pétersbourg*, 1904, janvier, XX, 44.

observation for both; the orbital velocities are computed in the same manner. Here is the table:

	log R	Δ log R	ω	$\Delta\omega$	H
R.........	9.976852–10	+0.000 010	$-107°\ 7'\ 56''$	+10″	31.12 km per sec.
Q.........	976945	+ 8	107 5 20	+34	31.68
B.........	977552	− 12	106 54 58	−28	35.12
C.........	978009	− 16	106 49 36	−20	37.50
W.........	978263	00	106 47 1	+20	38.76

Considering the difficulties involved in measuring photographs of comet tails, we may well conclude that the hyperbola, determined above, represents the observations satisfactorily. The theoretical velocities agree likewise sufficiently with the velocity 34.3 km as derived from the observations.

After the theoretically derived instant of emanation, M_0, the comet was observed on the same day, July 23, by Barnard and Curtiss, but nothing of the phenomenon of July 24 was to be seen; because the matter of the end of the tail (sent out from the nucleus at an angle of $G=-21°.5$ to the radius vector when the nucleus had an anomaly $v_0=-108°\ 15'\ 19''$ with an initial velocity of 55.2 km in the hyperbola) entered the comet's orbit at an angle of $3°\ 13'.5$; it therefore moved almost in the same direction with respect to the Sun as the nucleus. It was not until five hours later, at the anomaly $-108°\ 2'\ 12''$ and with an orbital velocity already diminished to 46.7 km that it again emerged from the comet's orbit, and then still continued its motion toward the Sun in the neighborhood of the nucleus. Three and five hours, respectively, after this egression the comet was photographed by Barnard and by Curtiss with velocities of 42.3 and 38.8 km. The orbital velocity of the nucleus increased from 43 km for M_0 to 43.2 for the moment of Curtiss' plate. On account of the continuous motion of the tail, which was almost in the same direction as that of the nucleus, it was in close proximity Δ to the nucleus when photographed by Barnard and Curtiss. Δ was smaller than the radius of the nebulous envelope. From the computation of the hyperbola, we find $14.35\ \Delta_{\text{Ba.}}$ (July 23) $=\Delta_{\text{Ba.}}$ (July 24), (1 mm = 10′), as measured on the photographs. Considering the slightly smaller distance between Earth and comet on July 23,

the distance in question will be about 1.2 mm (1 mm = 8′.9). The diameter of the nebulous envelope on July 23 in the direction of the radius vector is 5 mm on Barnard's photograph, and 4 mm perpendicular to this direction. The end point of the tail, which is entirely separated from the nucleus, is therefore inside this envelope and invisible. The same holds true of the photograph of Curtiss on July 23. For July 23 Δ is 15.53 times smaller than the δ on C.'s plate for July 24. It amounts therefore to $s = 11'.0$, measured from the nucleus; this corresponds to 2.65 mm on the plate of July 23 (1 mm = 4′.2), while the diameter of the envelope in the direction of the radius vector on the same plate is 15 mm, and 11 mm perpendicular to this direction. Distinct traces are noticeable on the plates of both Barnard and Curtiss (of July 23) of another end of the tail, which was separated before the one in question—about July 22.4792 G. M. T.

The tail under consideration was therefore also photographed on July 23, although, of course, it had not yet the length which it gained on the following day. This agrees well with the theory of cometary forms. Indeed, a hyperbolic motion, especially with a large repulsive force, will produce in a short time an immense extension and dissipation of the matter constituting the tail, since matter separated from the comet at an earlier epoch which is farther away from the nucleus will have a much larger orbital velocity than the other. On July 25 the comet was photographed by Barnard and also by Curtiss. Both plates fail to show the end of the tail, since, as the theory shows, it was either outside of, or on the very edge of, the exposed part. Furthermore, it had now attained a velocity of 74.5 and 81.9 km, respectively, so that, on account of resulting wide dissipation in space, the action of the particles was too weak to produce an impress on the plate. The orbital velocity is increasing continuously, and its limiting value of 406.8 km is reached in infinity.

To afford a better view of the matter we have tabulated the quantities R, ω, Δ, H of the tail and r, v, and h (orbital velocity) for the nucleus. Besides, to facilitate a graphical construction, we have given the co-ordinates ξ_{comet}, η_{comet} of the nucleus, and ξ_o, η_o of the end of the tail. They are referred to a system of axes which is immovable and pertains to the epoch M_o. (In the table the designation "egress" is the egress out of the orbit of the comet.)

		1903 G.M.T.	r	R	v	ω	h	H
1..	Emanation	July 23.3636	0.96019	0.96019	−108°15′.3	−108°15′.3	43.0	55.2 km per sec.
2..	Egress	23.5757	0.95592	0.95515	−108 4.2	−108 2.2	43.1	46.7
3..	Barnard	23.6972	0.95348	0.95285	−107 57.8	−107 54.6	43.1	42.3
4..	Curtiss	23.8036	0.95134	0.95118	−107 52.2	−107 48.0	43.2	38.8
5..	Perihelion	24.2868	0.94158	0.94775	−107 26.3	−107 17.5	43.4	30.2
6..	Roberts	24.4382	0.93852	0.94809	−107 18.1	−107 7.9	43.4	31.1
7..	Quénisset	24.4792	0.93769	0.94830	−107 15.8	−107 5.3	43.5	31.7
8..	Barnard	24.6438	0.93436	0.94963	−107 6.8	−106 55.0	43.5	35.1
9..	Curtiss	24.7292	0.93263	0.95062	−107 2.1	−106 49.6	43.6	37.5
10..	Wallace	24.7701	0.93180	0.95118	−106 59.8	−106 47.0	43.6	38.8
11..	Barnard	25.6633	0.91366	0.97528	−106 9.4	−105 52.2	44.0	74.5
12..	Curtiss	25.8334	0.91020	0.98241	−105 59.6	−105 42.1	44.1	81.9

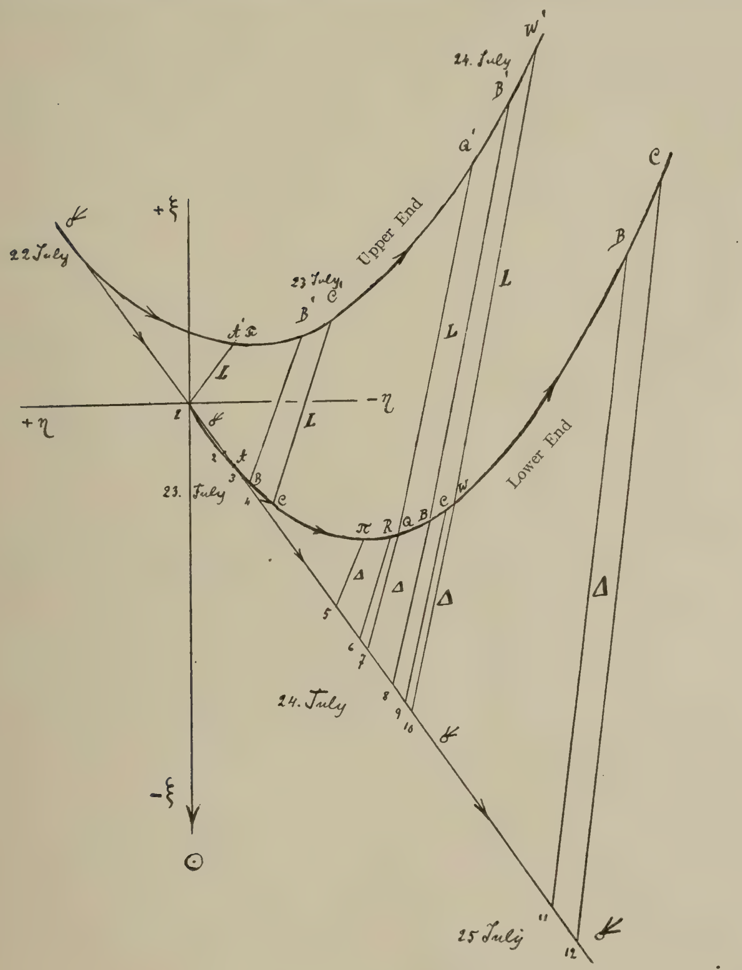
	ξ comet	η comet	ξ_0 (obs.)	η_0 (obs.)	Δ (obs.)	ξ_0 (com.)	η_0 (com.)	Δ (com.)
1	0.00000	0.00000	0.00000	0.00000	0.00000	....	....	....
2	−0.00427	−0.00309	−0.00506	−0.00365	0.00096	....	....	....
3	−0.00673	−0.00485	−0.00736	−0.00574	0.00109	....	....	....
4	−0.00888	−0.00640	−0.00904	−0.00757	0.00118	....	....	....
5	−0.01871	−0.01343	−0.01257	−0.01594	0.00663	....	....	....
6	−0.02180	−0.01563	−0.01228	−0.01859	0.00997	−0.01230	−0.01854	0.00994
7	−0.02264	−0.01623	−0.01209	−0.01930	0.01099	−0.01211	−0.01915	0.01094
8	−0.02602	−0.01862	−0.01083	−0.02220	0.01560	−0.01081	−0.02232	0.01566
9	−0.02778	−0.01986	−0.00986	−0.02370	0.01832	−0.00983	−0.02379	0.01837
10	−0.02862	−0.02046	−0.00933	−0.02443	0.01970	−0.00932	−0.02434	0.01968
11	−0.04714	−0.03344	+0.01423	−0.04061	0.06179	....	....	....
12	−0.05070	−0.03592	+0.02124	−0.04378	0.07237	....	....	....

The accompanying figure gives us an adequate idea (1 astronomical unit = 2000 mm) of the relative motion of the comet's tail with respect to the Sun, and also of the motion of the nucleus during this time. It will be noticed how well the computed arc represents the observed one, and it likewise becomes apparent why the end of the tail is invisible on the plates of July 23 and July 25, 1903.

Mr. S. A. Mitchell states in his article "Comet Borrelly and Light Pressure,"[1] that the velocity of the end of the tail on July 24 was 407 miles (= 655 km) with respect to the Sun. We have seen before that parts of the comet which are nearer to the nucleus will have an orbital velocity different from that of parts which are farther off. Although we may not speak of a velocity of the comet's tail, we may well speak of the velocities of different parts of it. On the other hand, such a velocity as Mr. Mitchell obtains is incomprehensible, since it is wholly incompatible with that velocity which we obtained for the end of the tail. Neither has the end of the tail farther away from the Sun the velocity attributed to it by Mr. Mitchell. Indeed, it is quite possible from the available plates to obtain approximately the orbit of the end farther away from the Sun which has been visible.

[1] *Astrophysical Journal*, **20**, 68, 1904.

The ejection of this matter took place July 22.4792 G. M. T. at an angle $G = -40°$ and initial velocity $g = 0.45$ (13.4 km). That g and G are in this case larger is amply indicated by Quénisset's plate, from



which plate we conclude that the separated tail has a considerable curvature (in the orbit of the comet), the concave side of which is turned forward (in the direction in which the nucleus is moving). The entire tail is ahead of the radius vector when prolonged (ϕ is counted negative for all its points) in such a manner that the end

farther away from the nucleus ($\Delta = 0.04585$, $\phi = 11^\circ\ 52'.8$) is about 3.5 times farther away from the prolongation of the radius vector than that end of the tail which is closer to the nucleus ($\Delta = 0.01094$, $\phi = -14^\circ\ 31'.1$). With due consideration for these and similar facts, the following hyperbolic elements have been obtained:

$M_0 = 1903$ July 22.4792 G. M. T. $M_\pi = 1903$ July 23.4035 G. M. T.
$1-\mu = 89.05$ $g = 0.45$ $G = -40^\circ$ $\log A = 9.680853-10$
$\log P = 8.134034-10$ $\psi = 9^\circ\ 33'\ 50''$
$\log Q = 9.984969-10$ $\omega_\pi = 107^\circ\ 56'\ 56''$
$\log E = 0.006079$

By means of this system we obtain:

	1903 G. M. T.		R	ω	ξ_0	η_0	Δ	H
1..	Emanation	July 22.4792	0.97795	$-109^\circ\ 0'.5$	+0.01767	+0.01287	0.00000	55.9 km per sec.
2..	[Emanation]	23.3636	0.96601	$-107\ \ 59.7$	+0.00580	−0.00439	0.00727	34.0 "
3..	Perihelion	23.4035	0.96598	$-107\ \ 56.9$	+0.00577	−0.00517	0.00800	33.9 "
4..	Barnard	23.6972	0.96721	$-107\ \ 36.6$	+0.00695	−0.01090	0.01496	36.8 "
5..	Curtiss	23.8036	0.96825	$-107\ \ 29.2$	+0.00797	−0.01299	0.01809	39.1 "
6..	Quénisset	24.4792	0.98228	$-106\ \ 43.1$	+0.02173	−0.02634	0.04551	61.9 "
7..	Barnard	24.6438	0.98761	$-106\ \ 32.1$	+0.02697	−0.02964	0.05412	68.5 "
8..	Wallace	24.7701	0.99220	$-106\ \ 23.8$	+0.03148	−0.03219	0.06124	73.6 "

The moment 2 [emanation] refers to the end of the tail nearer to the nucleus, which took place about twenty-one hours after the first. The co-ordinates ξ_0, η_0 are given on the drawing, using the same scale; they are marked "upper end." From the diagram it is apparent that the length L of the tail in which we have been interested is continuously increasing on account of the varying orbital velocities in the different parts of the tail. For convenience we have put together in tabular form the theoretical values of Δ and H for both ends of the tail, and likewise the values for L:

	1903 G. M. T.	Δ		L	H	
		Beginning	End		Beginning	End
[Emanation]......	July 23.36	0.00000	0.00727	0.00727	55.2 km per sec.	34.0 km per sec
Barnard	23.70	0.00109	0.01496	0.01490	42.3 "	36.8 "
Curtiss..........	23.80	0.00118	0.01809	0.01800	38.8 "	39.1 "
Quénisset........	24.48	0.01099	0.04551	0.03452	31.7 "	61.9 "
Barnard.........	24.64	0.01560	0.05412	0.03847	35.1 "	68.5 "
Wallace..........	24.77	0.01970	0.06124	0.04155	38.8 "	73.6 "

We can see from the following considerations that the second hyperbola represents approximately the motion of the more remote end of the tail. On both of the plates of Curtiss, dated July 23 and

24, the length of the visible tail (July 23) is almost equal to the distance between the tail end and nucleus (July 24); the same holds true for $L=0.01800$ (July 23) and $\Delta=0.01837$ (July 24). For the photograph of Quénisset (July 24) the theoretical value $\Delta=0.0455$ agrees likewise with the observed value. On account of the continuous spreading out of the tail its light grows weaker and weaker, and this is clearly the case on the plates of Curtiss and Wallace on July 24.

On July 24 the mean velocity of the end nearer to the nucleus is 34 km, while the end farther away has one of 68. Averaging the two, we may call 51 km the mean velocity of the entire tail, but never 655 km!

Neither can the method by which Mr. Mitchell obtains a determination of $1-\mu$ furnish accurate results. He uses the angle ϕ for this purpose and derives separate values for $1-\mu$ for the months of June, July, and August. It is in itself an inaccurate proceeding, which suffers still more for values of the tail which are but slightly deflected from the radius vector, and more yet for values of the anomaly larger than 90°,— which indeed was the actual case in June and July. Employing the value zero for the initial velocity g, as Mr. Mitchell has done, his method is correct only for points on the axis of the conoid. Such points are generally not the ones which are being observed; it is rather the forward or the backward branch of the conoid which comes to be observed. Using the method mentioned above as Mr. Mitchell does, he must obtain a value for $1-\mu$ which in the first case is considerably larger, and in the second case considerably smaller, than that which holds true for the axis. But $1-\mu$ should have the same and constant value for all of the three cases. Even an emanation which takes place exactly in the direction toward the Sun will in larger measure pass over into the forward branch; and when G has negative values, the forward branch may happen to be the only one which takes place (especially in cases where tails of the first type occur), while the backward branch may vanish to invisibility. By neglecting g we obtain even for the central axis of the tail a value for $1-\mu$ which is considerably too large.

The existence of such a velocity of emanation has been proved by Bredichin's investigations, which include more than fifty comets; and in the case of Borrelly's comet it is further evidenced by the

negative value of ϕ on June 22 and 26, and on July 20 and 24. These angles cannot be accounted for by values of $1-\mu$, no matter how large, for $g=0$; even $1-\mu=\infty$ will for $g=0$ lead to a limiting value of $\phi=0$. This is the reason why Mr. Mitchell discards these observations, upholding his idea by the words: "It is impossible for the comet's tail to be ahead of the radius vector."

More accurate and concordant results might have been derived by Mr. Mitchell, if Albrecht's angle between tail and prolonged radius vector had not been employed. Strictly speaking, such angles do not exist; at most they indicate the initial or general direction of the tail; and that will not suffice for the accurate determination of $1-\mu$, especially with large values of the anomaly. That such angles do not exist can be seen from the fact that the tails have always a more or less marked curvature (after an accurate reduction upon the plane of the comet has been effected). To obtain more accurate values of $1-\mu$, it is necessary to select points of the tail which are as far as possible away from the nucleus, and from these we must determine values for ϕ and Δ. For the same reason Curtiss' values of $\phi=u-u_0$ cannot be used for the determination of $1-\mu$ ("of the angle in the orbital plane of the comet between the radius vector from the Sun and the axis of the tail.")[1] Besides, as we have already stated, all these angles are not referred to the axis of the conoid of the tail, at least not the negative values.

On the plates of Roberts and Quénisset (July 24) there is another branch of the tail, between the tail which is separated from the nucleus and the radius vector when prolonged. There are two points, one near the middle, the other at the very end, of the branch for which $\phi=-5°14'.3$, $\Delta=0.01181$ and $\phi=-0°54'.1$ and $\Delta=0.02442$. For the representation of this branch it suffices to take $g=0.2$, $G=-8°$, and $1-\mu=18$. The tail which is behind the radius vector belongs to type III. Its end points have for co-ordinates $\phi=+14°\ 41'.4$, and $\Delta=0.02706$, $1-\mu=0.2$. Another streamer, which is bent still more, has for co-ordinates of the end point $\phi=+25°\ 1'.4$, $\Delta=0.00676$; to it belongs $1-\mu=0.025$. The second type was not present. Still Mr. Mitchell finds one of this kind with $1-\mu=2.2794$, notwithstanding that the value of ϕ which enters into the computation is

[1] *Lick Observatory Bulletin* No. 42, p. 102.

$+18°$, i. e., much larger than the value of ϕ for the end point of the tail of type III. It is now quite easy to explain the values of $1-\mu$ for the first type. They vary without regularity from 3.5 to 114.9 during three months—a phenomenon not heretofore observed in any comet.

Mr. Mitchell says: "The light-pressure theory makes it plain why the angles between the radius vector and the tail continually increase up to the perihelion."[1] This well-known fact is simply a consequence of the motion of the nucleus on a conic and of the simultaneous motion of matter, emanating from the nucleus, and acted upon by a repulsive force located in the Sun which is inversely proportional to the square of the distance. From the mechanical phenomenon just related it is impossible to draw conclusions as to the physical nature of this force.

It is quite possible that the light-pressure as a repulsive force plays some important rôle in the formation of comets' tails, but in the case of Borrelly's comet it has not been proved that the light-pressure has acted in the sense of Arrhenius' theory, since the motion of the tail, investigated above, requires the assumption of a repulsive force sixty times greater than gravity. But this is what Mr. Mitchell has assumed. If we want to retain the hypothesis of light-pressure, we should have to maintain, on account of Schwarzschild's investigations, Bredichin's idea that the matter of the tail consists of gas molecules. These gas molecules, according to Lebedew,[2] are probably under the influence of a repulsive force exerted by the rays of the Sun, although it has not been possible to demonstrate this experimentally. The cause for the luminosity of comets' tails can thus be understood to be the fluorescence of highly illuminated gases, and this has been demonstrated experimentally by Lommel, Wiedemann, and Schmidt.

Repulsive forces were found to exist by Bredichin[3] in the case of Comet Rordame 1893 II ($1-\mu=36$), and by W. H. Pickering[4] in the case of Comet Swift ($1-\mu=39.5$). The existence of such forces proves the untenability of the light-pressure theory, from the stand-

[1] *Astrophysical Journal*, **20**, 67, 1904.

[2] *Physikalische Zeitschrift*, **4**, 17, 1902.

[3] *Bull. de l'Acad. Imp. des Sciences de St. Pétersbourg* T. II, 392, 1895.

[4] *Annals of Harvard College Observatory*, **32**, Part II, 1286.

point of the hypothesis of Arrhenius. Pickering's result is confirmed by preliminary investigations of the writer concerning the motion of the denser parts of the tail of Comet Swift 1892 I. They are carried out by means of the rigorous formulas for hyperbolic motion, and lead to the postulate that $1-\mu$ is certainly larger than 20.

On page 64 of Mr. Mitchell's paper there is this remark: "The electrical force, on which Bredichin explains his repulsions, has been shown by Lebedew not to have a sound physical basis." Against this statement this is to be said: Long before Lebedew, Bredichin admitted the possibility that the unknown repulsive energy of the Sun may well be of other than electrical character. In 1879 Bredichin expressed himself thus:

J'emploie la dénomination de l'électricité pour l'énergie, qui émane du soleil et agit diversement sur les différents éléments chimiques des comètes, parceque cette dénomination est déjà introduite dans les théories physiques des comètes; mais il est bien possible, que les recherches ultérieures préciseront mieux la dénomination et les qualités de cette énergie.

Kepler guessed at the hypothesis of a light-pressure and Maxwell's famous investigations on the electromagnetic theory of light induced Fitzgerald, Lodge, and others to bring the light-pressure theory again into the foreground of scientific interest. It was then (1894) that Bredichin collected his ideas in the following statement:

L'admission d'une charge électrique devient un peu risquant en égard aux nouveaux points de vue sur l'essence même de l'électricité, comformément aux quels la force répulsive électrique dans les queues sera peut-être regardée comme l'action répulsive des corps rayonnants.[1]

Moscow, December 29, 1904.
January 11, 1905.

[1] Bredichin–Jaegermann, pp. 483, 484.

ON THE ENHANCED LINES OF IRON, TITANIUM AND NICKEL

By F. E. BAXANDALL

The results of a detailed study of the enhanced lines of iron, titanium, and nickel have recently been published by Dr. H. M. Reese.[1] In the case of each of the first two metals, he has compared the lines with those published by Sir Norman Lockyer,[2] and given rather lengthy lists of additional enhanced lines which do not appear in that record.

The importance of the enhanced lines of these metals in their relation to well-marked lines in certain types of stellar spectra has suggested an analysis of these extra lines being made, and an investigation of their authenticity as enhanced lines in the ordinary acceptation of the term.

IRON

A table has been prepared which gives, in addition to Reese's spark and arc intensities, those of Exner and Haschek (spark) and Kayser and Runge (arc), extracted from Watts' *Index of Spectra.* In each case an intensity-range of 1 to 10 is used, so that the relative intensity in spark and arc ought to be roughly comparable. One would naturally expect, if Reese's extra lines are really enhanced, that Exner and Haschek's spark intensities would, in the majority of cases, be greater than those of Kayser and Runge, for the corresponding arc lines. So far is this from being the case, however, that only one of the sixty-five extra lines which can be compared in this way (five of Reese's lines are beyond Exner and Haschek's limits) fulfils that condition. This particular line (4303.34) was accidentally omitted from the Kensington record in preparing the paper for press, and has, since the publication of the enhanced line paper, been quoted in several Kensington publications.[3] There is no doubt whatever as to this being a genuine

[1] *Astrophysical Journal*, **19**, 322, 1904. [2] *Proc. R. S.*, **65**, 452, 1899.

[3] *Phil. Trans.*, A, **197**, 218, 1900. *Ibid.*, **201**, 218, 1904.

enhanced line, and it has its counterpart in many stellar spectra (notably *a Cygni*) and in the chromospheric and Fraunhoferic spectra.

With regard to the remaining sixty-four lines in Reese's record, this test, at any rate, tends to show that they cannot be accepted as enhanced lines. Such a test, however—the comparison of the published records of two different observers—is not so adequate and conclusive as a direct comparison of the spark and arc spectra. The identical negatives from which the Kensington record of enhanced lines was reduced have therefore been carefully re-examined, and the behavior in them of Reese's extra lines has been investigated. In the table given later, the last column is reserved for remarks on the occurrence and behavior of these lines in the Kensington arc and spark photographs.

Of the seventy lines, fifteen are stronger in arc than in spark, twenty-five are equally strong in both spectra, twenty do not occur in either spectrum, while six are slightly stronger in spark than arc, but are so nearly equal that one does not feel justified in recording them as enhanced lines: Three are outside the range of the Kensington grating photographs. The remaining one (λ 4303.34), which is well enhanced, has previously been referred to and its absence from the published Kensington record explained.

Four of the most enhanced lines in Reese's extra list are λλ 4311.07 (2–3, tr.), 4322.92 (3, tr.), 4380.67 (3, tr.), and 4386.77 (3, tr.). There is not the slightest trace of these lines in any of the Kensington iron spectra, and none of them is recorded by Exner and Haschek.

It may be remarked that among Reese's extra lines such well-known strong spark and arc lines as the triplet λλ 4383.72, 4404.93, 4415.29 occur. These have been repeatedly used in Kensington publications as typical instances of the ordinary or unenhanced lines.

The inclusion by Reese of so many extra lines is probably due to the fact that he has selected a spark spectrum which has the majority of the lines slightly stronger than the corresponding lines in the arc. It would be possible, of course—to give an extreme case—so to arrange the relative exposures of the spark and arc photographs that all the spark lines might appear to be enhanced.

To be certain, however, of the lines being enhanced in the spark it is obviously best to give a slight bias to the arc lines in general; that is, to select the photographs so that the majority of lines are, if anything, slightly stronger in the arc; then any lines which are intrinsically stronger in the spark, after that preliminary condition has been fulfilled, may be legitimately accepted as enhanced lines.

Reese specially states that there is only one line stronger in his arc than in his spark photograph. This fact alone is nearly sufficient to show that he has, no doubt unconsciously, given a slight bias to the spark lines in general, so far as intensity is concerned, and explains the appearance in his record of so many extra lines. These are doubtless slightly stronger in his spark spectrum, but they cannot be unreservedly accepted as enhanced lines in the sense in which the term was first used.

There are five lines in Sir Norman Lockyer's list which Reese mentions as not appearing in his photographs. These are λλ 4302.35, 4451.75, 4462.30, 4541.40, 4635.40. A re-examination of the Kensington photographs shows that, with the possible exception of 4302.35 (whose arc and spark intensities are so nearly equal that it might have been better to omit it from the list), they are undoubtedly enhanced, λ 4541.40 and 4635.40 especially being quite outstanding lines in the spark; and weak or lacking in the arc. Strangely enough, Reese quotes these two as being missing from his plates. They correspond to lines in the spectrum of *a Cygni*, similarly to the other well-enhanced iron lines, so that there is apparently no reason to doubt their authenticity.

Reference to the plate.—In the plate at the end of the paper, the spark and arc-spectra of iron are reproduced.

The photographs were taken with a four-prism Steinheil spectroscope, the large Spottiswoode coil being used to obtain the spark. The enhanced lines are conspicuously shown.

The lines marked L are some of the typical lines which appeared in Sir Norman Lockyer's list, and it will be seen that they are most distinctly stronger in the spark, although the majority of the lines are somewhat stronger in the arc.

The lines marked R are a few of those given by Reese in his

ANALYSIS OF REESE'S EXTRA ENHANCED *Fe* LINES

a=stronger in arc spectrum. *b*=equally strong in spark and arc. *c*=lacking both in arc and spark.

Reese			Exner & Haschek (Spark)	Kayser & Runge (Arc)	Remarks on Behavior in Kensington Photographs
λ	Intensity				
	Spark Max. 10	Arc Max. 10	Int. Max. 10	Int. Max. 10	
4219.52	3–4	3	6	8	Slightly stronger in spark
4220.50	1	tr	2	4	*b*
4226.11	1	tr	1	4	*a*
4226.58	1	tr	1	4	*a*
4229.69	tr	..	1	2	Slightly stronger in spark
4230.54	tr	..	..	1	*c*
4230.86	tr	..	..	1	*c*
4240.53	1	..	1	2	*b*
4242.89	tr	..	1	2	*b*
4246.24	1	..	2	4	*b*
4250.96	6	5	8	10	*b*
4253.90	1	..	..	1	*c*
4268.94	3	tr	1	4	*b*
4271.94	7	6	10	10	*b*
4274.90	2	1	..	2	*a* ? *Cr* impurity
4277.88	1	..	..	1	*c*
4279.60	tr	..	1	1	*c*
4285.59	1–2	1	2	6	Slightly stronger in spark
4288.32	tr	..	1	4	*b*
4290.50	tr	..	1	2	*b*
4296.08	tr	..	..	1	*c*
4298.21	2	1	1	4	*b*
4303.34	1	..	2	1	Accidentally omitted from Kensington record in preparing paper for press
4307.53	1	..	..	..	*c*
4308.08	8	7	10	10	*b*
4309.20	1	tr	2	2	*b*
4310.28	tr	..	...	..	*c*
4311.07	2–3	tr	..	1	*c*
4322.92	3	tr	..	1	*c*
4325.95	8	7	10	10	*b*
4328.95	2	tr	..	1	*c*
4331.96	1	..	..	1	*c*
4343.45	tr	..	1	2	*b*
4343.89	tr	..	1	2	*b*
4346.73	tr	..	1	4	*b*
4367.75	2	1–2	2	6	*b*
4371.52	1	tr	..	1	*c*
4373.75	tr	..	1	2	*b*
4380.67	3	tr	..	1	*c*
4383.73	10	9	10	10	*b*
4386.77	3	tr	..	1	*c*
4388.06	1	tr	2	4	*b*
4388.58	1–2	1	2	6	*a*
4390.05	tr	..	..	2	*a*

ANALYSIS OF REESE'S EXTRA ENHANCED *Fe* LINES—*Continued*

Reese λ	Reese Intensity Spark Max. 10	Reese Intensity Arc Max. 10	Exner & Haschek (Spark) Int. Max. 10	Kayser & Runge (Arc) Int. Max. 10	Remarks on Behavior in Kensington Photographs
4391.12......	1	tr	1	6	*b*
4392.68......	tr	..	1	1	*c*
4401.46......	1	tr	1	6	Slightly stronger in spark
4404.93......	9	7–8	10	10	*b*
4407.99......	2–3	..	2	6	*b*
4412.22......	2	tr	..	2	*c*
4415.32......	7	6–7	8	10	*b*
4418.36......	2	..	..	1	*c*
4423.98......	1	..	..	1	*c*
4433.38......	2	1	2	6	*a*
4450.51......	1	..	1	2	Slightly stronger in spark
4466.72......	4	3–4	5	8	*b*
4477.43......	1	..	..	1	*c*
4548.02......	1–2	1	2	8	*b*
4598.30......	tr	..	1	6	*a*
4619.46......	1	tr	1	6	*a*
4637.69......	1	tr	1	6	*a*
4638.21......	1	tr	1	6	*a*
4669.34......	tr	..	1	4	*a*
4673.36......	tr	..	1	4	*a*
4691.59......	1	tr	1	6	*a*
4786.99......	1	tr ?	Beyond Exner & Haschek's range	4	*a*
4789.83......	1–2	tr		6	*a*
5002.05......	2	1		8	Beyond the range of the Kensington grating photographs
5005.90......	2	tr		6	
5006.31......	2	1–2		8	

list of additional enhanced lines, but a glance at the plate will show that there is no indication of their being enhanced in the spark.

The two lines marked X are the Kensington lines which Reese says are missing from his plates. The absence of these two from his spectra is rather remarkable, especially as he seems to have photographed many lines which do not occur in the Kensington photographs at all.

TITANIUM

In the case of titanium, Reese gives twenty-five lines in addition to those in the Kensington list, six of them, however, being outside the range of the latter. As to the remaining nineteen lines, reference to the photographs from which the Kensington reductions were made, failed to substantiate them as enhanced lines. A much

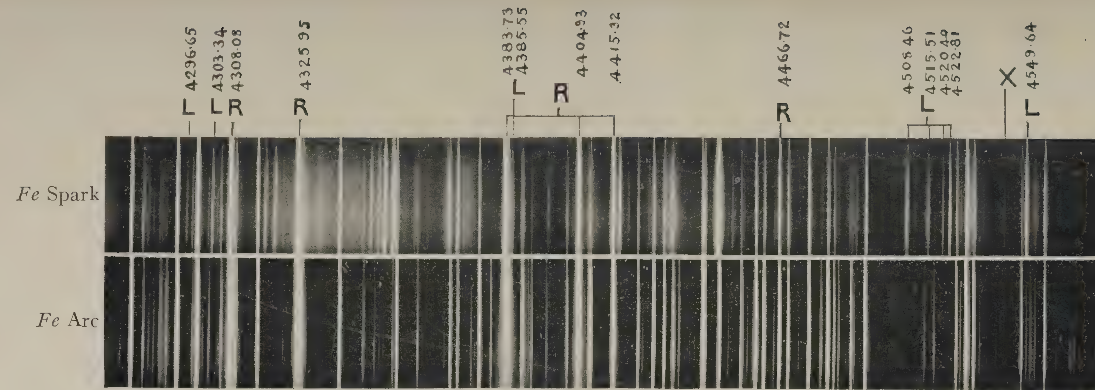
better and more extensive titanium spark photograph has been recently obtained, and an investigation of this shows that twelve of Reese's nineteen lines are stronger in the spark spectrum than in the arc, though most of these are very weak, even in the spark. Of the other seven, five are entirely lacking in both spark and arc spectra (three of these five are also missing from Exner and Haschek's record), one is appreciably stronger in arc than spark, and one is equally strong in spark and arc. All these are indicated in the accompanying table.

With regard to the Kensington line λ 4308.60, which Reese says is probably identical with his λ 4308.06, it may be said that the former published wave-length was an erroneous one. It should

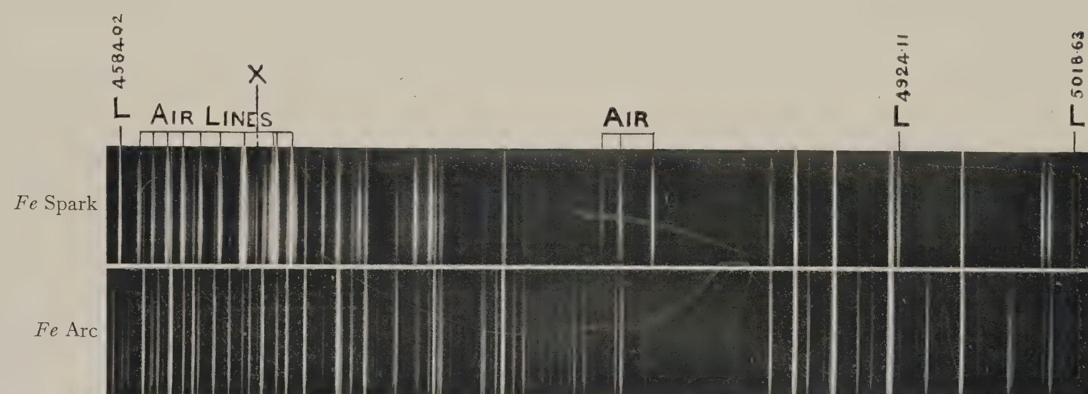
ANALYSIS OF REESE'S EXTRA ENHANCED *Ti* LINES

a = stronger in spark. *b* = lacking both in spark and arc.

Reese			Exner & Haschek Intensity		Remarks on Behavior in Kensington Photographs
λ	Intensity				
	Spark Max. 10	Arc Max. 10	Spark Mx. 100	Arc Max. 20	
4288.04	3	2	2	1	*a*
4305.07	3	2	..	..	*b*
4337.56	2–3	tr	1	..	*a*
4398.24	2–3	2	..	..	*b*
4398.45	2	1	1	..	*a*
4409.40	2–3	1	1	..	*a*
4409.68	2–3	1–2	1	..	*a*
4412.09	2–3	1	1	..	*a*
4418.50	4	3	2	..	*a*
4432.27	2	tr	1	..	*b*
4440.88	2	1	..	..	*b*
4441.89	3	2	..	..	*a*
4444.72	3	2	1	..	*a*
4456.81	2	..	1	..	*a*
4471.02	3	2	2	1	*a*
4537.35	4	3	1	1	Stronger in arc
4544.18	3	2	1	..	Equally strong in spark and arc
4568.49	2–3	1	1	..	*a*
4583.59	2	1	1	..	*b*
4609.55	4	3	1	1	1. These lines are outside the limits of those published by Sir Norman Lockyer. Reference to a more recent and unpublished Kensington reduction shows that Nos. 2, 4, 5, and 6 are certainly enhanced. Nos. 1 and 3 are not enhanced in the Kensington photographs
4657.37	3	1	1	..	2.
4687.98	2	1	1	..	3.
4764.08	4	2	Beyond Exner & Haschek's range		4.
4805.26	4	2			5.
4911.39	5	1			6.



REGION 4275-4580



REGION 4580-5030

have been λ 4308.10, the mistake probably being due to a transcriber's error in copying the paper for press. The corrected wave-length has been used in subsequent Kensington publications.[1]

NICKEL

This metal was not one of those for which a record of enhanced lines was given in Sir Norman Lockyer's publication. The enhanced nickel lines have, however, since been reduced, as well as those of many other metals, and will be included in a future publication. The Kensington list has been compared with that given by Reese for the same element. Of the lines in the latter list λλ 4244.94, 4279.36, 4362.28, and 4509.42 are enhanced in the Kensington photographs, but there is no indication of the enhancement of the lines at λλ 4231.22, 4297.15, 4298.70, 4307.05, 4368.49, and 4398.66. It is only fair to say, however, that the enhancement of these in Reese's photographs is according to his spark and arc intensities, only very slight.

For each of the metals named Reese gives a further list of additional lines which he has not been able to find in any of the published records relating to the same metals. In view of this fact, it is extremely unlikely that they are genuine lines of the metals specified, and it has not been thought worth while to analyze them in the same way as the lines which have previously been recorded by other observers.

I must express my indebtedness to Sir Norman Lockyer for permission to use the excellent photographs involved in the discussion, and to Mr. C. P. Butler, who obtained them; some of these were taken with a large concave Rowland grating, and those reproduced in the plate with a four-prism Steinheil spectroscope.

SOLAR PHYSICS OBSERVATORY,
SOUTH KENSINGTON,
March 7, 1905

[1] *Phil. Trans.*, A, **197**, 218, 1900; *ibid.*, A, **201**, 218, 1904.

NOTE ON THE CONDITIONS ATTENDING THE APPEARANCE OF THE ARGON LINES IN AIR

By A. S. King[1]

The spectrum of argon in gas mixtures was shown by Collie and Ramsay[2] to be not especially sensitive when a Geissler tube containing the mixture was excited by the ordinary glow-discharge, 37 per cent. of argon in nitrogen being required to show the argon spectrum. This was correct, however, only for the experimental conditions used by these observers, as Crookes[3] had previously shown that the argon in the air (less then 1 per cent.) would show its spectrum when atmospheric nitrogen was subjected to long-continued discharge in a tube with platinum electrodes, the nitrogen being for the most part removed by the electrodes. Newell[4] showed the same for ordinary air when the nitrogen was removed by passing a discharge through it in the presence of sulphuric acid and hydrogen or water vapor, the pressure in the tube becoming very low thereby. Further, Hartley[5] found that the spectrum given by copper, aluminium, or platinum electrodes in open air showed a number of lines which agreed very closely with lines in the argon spectrum and did not appear to belong to oxygen or nitrogen.

Lilienfeld showed in some recent experiments[6] that when an unusual discharge arrangement was used with tubes having outside electrodes and containing air at a pressure as high as 30 mm, the blue spectrum of argon appeared with the line spectrum of air. This gave promise of being a method of increasing the sensitiveness of gaseous spectra in general, and at the suggestion of Professor Warburg I undertook some experiments to determine the essential features of the spark-discharge needed to give the argon spectrum this degree of sensitiveness.

The discharge circuit used by Lilienfeld was first tried, and is

[1] Research Assistant of the Carnegie Institution of Washington.

[2] *Proc. R. S.*, **59**, 275, 1896.

[3] *Ibid*, **57**, 287, 1895.

[4] *Ibid.*, **57**, 346, 1895.

[5] *Ibid.*, **57**, 293, 1895.

[6] *Sitzungsberichte der K. Akademie der Wiss. zu Berlin*, 1904, p. 1196.

shown in Fig. 1. The terminals of an induction coil are connected to a battery of two or three Leyden jars in cascade which discharge across a spark-gap and through a self-induction spool of thick copper wire. In parallel with part or all of this self-induction is a tube having outside electrodes of tinfoil and containing air at about 3 mm pressure. The induction coil used gave a spark of about 25 cm in air, and was driven by either a Wehnelt or a mercury turbine interrupter. The currents used varied from 15 to 25 amperes and were supplied by a 110-volt dynamo circuit.

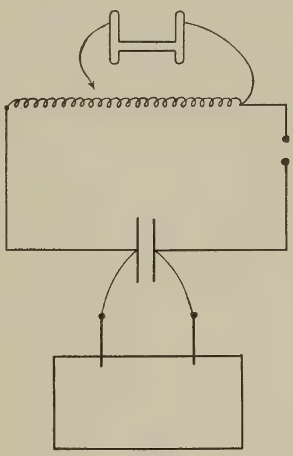


FIG. 1

It will be seen that this arrangement allows of considerable variation of the discharge through the tube, this discharge depending not only on the action of the Ruhmkorff and the capacity used, but on the amount of self-induction with which the tube is in parallel. The condenser gives an oscillating discharge, and a variable amount of this oscillating E. M. F. may be thrown on the electrodes of the tube. Lilienfeld found that with a small capacity a discharge could be maintained through the tube when in parallel with 20–30 turns of the spool, that then the line spectrum of air appeared, and a number of argon lines could be detected, the discharge producing but slight heating of the tube. This result was confirmed by the writer. Two Leyden jars, each 10 cm in diameter and with coating 13 cm high, were connected in cascade, and a spark-gap 2–2½ cm long in air was used. The self-induction spool had turns 3.5 cm in diameter and wound with two turns to the centimeter. The spectroscope had five Rutherfurd prisms and gave a large dispersion. To identify the argon lines, a Geissler tube containing very pure argon was placed horizontally in front of the slit, as in the experiment of Lilienfeld, so that its spectrum and that of the air-tube showed side by side. This arrangement has advantages over the use of a reflecting prism, but error must be guarded against if the slit is wide or the lines very bright, as then the slight illumination of the whole slit by the hori-

zontal tube suffices to give extensions of the lines which might be taken for lines in the other spectrum. In this case so narrow a slit was used that no extensions were visible. The Geissler tube was driven by a small coil, and a Leyden jar and spark-gap could be adjusted to give either the red or the blue spectrum.

The argon lines given by the air-tube did not develop into distinctness until the discharge had passed for a minute or more, as was observed by Lilienfeld; but after this period a number of the stronger argon lines could be seen, those most favorable for visual observation being in the blue-green at $\lambda\lambda$ 4880, 4848, 4806, 4765, 4736, 4727. The simple apparatus and low capacity, with the small heating of the tube, were favorable features of the arrangement.

The apparent small mean current-density in the tube, as indicated by the slight heating, combined with the appearance of the line spectrum of air, pointed to the conclusion that the wire of the inductance spool carries almost the whole current, while the rapid oscillations produce momentary high values of the current in the tube, which give the stimulus needed to bring out the spectrum of a very small amount of a gas.

A series of modifications of the spark-discharge was then made by the writer. The tube with outside electrodes was connected directly in series with the spark-gap. The discharge passed, with the spark-gap slightly shorter than before, but the air-bands now appeared, the same primary current and small capacity being used as before. By increasing the primary current the discharge could be forced into giving a fairly pure line spectrum, but the argon lines did not appear with this spectroscope, in which intensity was sacrificed to dispersion. The arrangement was, at any rate, not so favorable as that of Lilienfeld when so small a capacity was used. But the connection with the tube in series with the spark-gap seemed to give a greater mean current-density, as indicated by the heating of the capillary and brightness of the discharge.

A large capacity was then used for a series of trials. Two jars, each 19 cm in diameter and coated to a height of 36 cm, were connected in cascade, giving a capacity very large compared to that of the vacuum tube. While the results can be easily explained in accordance with those of the previous experiment, the arrangement of Lilienfeld proved now not to be the most advantageous.

The greater quantity of electricity when large capacity was used caused a heating of the capillary when the tube was in parallel with self-induction, so that the 0.3 mm capillary employed in the previous trials could not be used. An end-on tube with capillary 0.5 mm in diameter was found to give the best results. With this discharge the impedance offered by the inductance spool of negligible resistance is such that a discharge passes through the vacuum tube when in parallel with only a half-dozen turns of the spool, with a spark-gap of 2.5 cm. With so few turns the band spectrum of air appears, and the tube discharge must be strengthened with more self-induction in parallel until the line spectrum appears alone. When this condition is reached, the current in the tube branch is such that the capillary becomes quickly hot and can be used with safety but a few seconds at a time. A number of argon lines now appeared distinctly without requiring an interval to develop. Those mentioned before and λ 4610 were the most conspicuous, while all strong lines in this region not too close to air lines could be readily perceived. The end-on tube adds greatly to the strength of the spectrum, but with this heavy discharge gives a strong continuous ground. Variations in the circuit were made to bring out the argon lines as well as possible. They were found not to be very sensitive, but appeared best with the strongest discharge that the tube would stand, while any approach to the band spectrum caused them to disappear.

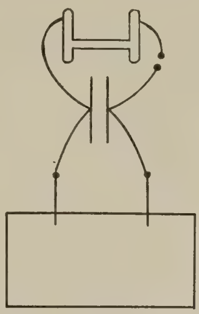


FIG. 2

The tube, with pressure unchanged, was then connected directly in series with the spark-gap (Fig. 2), and this was found with this capacity to give better results. The large capacity was able to maintain a discharge that was probably oscillatory, and with the turbine interrupter gave a thick, noisy spark 14 mm long between the knobs of the spark-gap in series with the tube. A bright discharge passed through the tube, and the two drawbacks of the arrangement with the tube in parallel, the heating of the capillary and the continuous spectrum, were now done away with. The spectrum showed the argon lines very distinctly, fully as strong as under the most favor-

able conditions of the former discharge; while the continuous spectrum was now so weak that a number of weaker argon lines could be recognized which were previously concealed. The heating of the tube was now comparatively slight, the capillary becoming only moderately warm after a run of three minutes. This small heating effect and the weakness of the continuous spectrum indicate a considerably smaller mean current-density in the tube when it is simply in series with the spark-gap. It was shown, however, that the difference of potential between the coatings of the tube was now considerably greater than with the tube in parallel with the self-induction. This could hardly be stated without a test, as the spark-gap is so much longer with the inductance spool that there is more energy in the discharge circuit to draw from, though the whole E. M. F. is not on the tube. The difference of potential in the two cases was roughly tested by an adjustable spark-gap connected to the two coatings of the tube; and the spark passed continuously at a distance about 35 per cent. greater when the tube was in series.

With the arrangement of Lilienfeld, the inductance spool necessarily has considerable influence on the discharge of the jars; and to retain this effect the spool should be kept in circuit with the other arrangement, the tube merely being put in series with the spool instead of in parallel. When this was done, the spectrum was little altered from the condition with no spool, but the argon lines were not so distinct, due probably to an approach to the band spectrum of air, which is the well-known effect of self-induction in the discharge circuit.

The substitution of a Wehnelt interrupter for the turbine showed the same relation between the two arrangements of the spark circuit, but it was necessary to use a shorter spark-gap, and the lines were correspondingly weakened.

A tube with inside electrodes of aluminium and containing air at about 3 mm pressure was next tried in series with the spark-gap. When the condensed discharge was made strong enough to give the line spectrum alone, the argon lines were even brighter with this tube than with that having outside electrodes. The inside electrodes would, of course, have disadvantages in general work.

In addition, the observation of Hartley[1] was fully confirmed by

[1] *Loc. cit.*

obtaining the argon lines by the spark in open air between copper electrodes, by which a strong air spectrum is given. There was no difficulty in identifying a number of argon lines by the eye. A photograph of this spectrum was made with the aid of a prism-spectrograph kindly lent me by Dr. Kreusler, the spectrum from the argon Geissler tube being photographed beside that of the spark in air. The argon lines in the blue and green sufficiently separated from air lines were given distinctly on this plate.

A still better comparison was made by examining some photographs which I took of the spectrum given by copper electrodes in air with a one-meter Rowland grating in the University of Bonn. The dispersion and definition of these photographs was such as to allow of a very accurate identification. On several plates taken with a powerful discharge from a large Klingelfuess inductor and a condensed spark 1 cm long between copper electrodes in air, the argon lines appeared very clearly, and the identification was rendered still more certain by comparison with a negative of the blue spectrum of argon in a vacuum tube, taken with the same grating and lent to me by Dr. Konen, of Bonn. The following argon lines could be identified with certainty in the air spectrum: λλ 4880, 4848, 4806, 4765, 4736, 4727, 4658, 4610, 4579, 4545, 4426, 4401, 4379, 4278. Other argon lines in this region occurring so near air lines as to make their appearance in the air spectrum uncertain are λλ 4590, 4503, 4430, 4371, 4348, 4331, 4228, 4130, 4104. Some differences appear in the relative intensities of lines in the two spectra, λ 4658 being relatively weak in air and λλ 4482, 4266 either absent or extremely weak. Some differences of this sort would be expected from the very different discharges in the two cases.

The photographs made in Bonn show the argon lines best under the most powerful discharge conditions which I was able to produce, i. e., when the copper electrodes were at least 1 cm apart in air, with a thick, noisy spark. They appeared when either the middle of this spark or the region next to one pole was projected on the slit, somewhat stronger in the latter case. Visual observations pointing in the same direction were made during the present investigation by varying the separation of the electrodes in air. The lines were weak in the spark about 3 mm long, in which the discharge appeared almost

like an arc and was accompanied by rapid heating of the electrodes, as compared with the long and very noisy spark. While the current is, of course, different in these two cases, there can be little question that as the spark is lengthened and the discharge becomes more crackling the potential-gradient increases considerably faster than the current.

Summarizing the experimental results of Lilienfeld and myself, the essential condition to bring out the argon spectrum from very small quantities of the gas seems to be a high momentary value of the current-intensity produced by the conditions attending the oscillating discharge, by which the line spectrum of the air or other gas is given. Such a discharge, both in the experiments with vacuum tubes and with the spark in air, proved more favorable than the discharge in which a large mean current-density was given, but in which the value of the current is probably more uniform. In other words, the discharge must be such as to give for an exceedingly brief time a current-strength that could not be used continuously, and in this way give the greatest possible stimulus to the gas particles.

Without a more exact knowledge of the character of the spark-discharge under different circumstances, it would be mere speculation to say more than this, the purpose having been to use the argon spectrum as a test for the best conditions to make a very small percentage of a gas spectroscopically visible.

I wish to express my thanks to Professor Warburg for many helpful suggestions during these experiments.

Physical Institute, University of Berlin,
March 1905.

OBSERVATIONS WITH THE RUMFORD SPECTROHELIOGRAPH

By PHILIP FOX

The work with the Rumford spectroheliograph has been continued, with the aid of a grant from the Carnegie Institution of Washington to Professor Hale, throughout the year 1904, with no interruptions other than those caused by cloudiness. No changes have been made in the instrument since it was described in Volume III, Part I, of the *Publications of the Yerkes Observatory*. The general program of observations outlined there has been followed quite closely. On each clear day two plates were taken on the center of the H line, called H_2, and one on the edge of the H line toward the violet, called H_1. After these plates, which serve as a record, were secured, the observations were of a diversified character. Series of plates were taken with settings on different positions approaching the H line, ranging from λ 3952 to λ 3968.6, the object being to obtain more evidence on the question of levels. Many plates were obtained with increased dispersion on lines of the spectrum other than H. Prominence plates were taken with regularity during the latter part of the summer and through the autumn.

The series of H_2 plates shows a decided increase in activity over those of the year 1903. While there were few disturbed areas equal to that about the great spot of October 1903, every plate shows several smaller groups of flocculi, either associated with spots or detached. Nearly all of these plates have circular images, and they are being measured for a new determination of the solar rotation period at the height above the photosphere of the high-level flocculi. This determination will supplement the preliminary work on the Kenwood spectroheliograms, soon to be published by the Carnegie Institution. The same method of measurement, that of projecting the plates upon an adjustable ruled globe by means of an arc lamp and suitable lenses, is being employed.

The series of plates taken with different settings gradually approaching the center of the H line are of interest because they bear on the question of levels and the expansion of calcium vapor as it rises above the general mass of condensed vapors. Exposures with five or six different settings are made on one plate by moving the second slit, as a whole, by means of a micrometric screw. Often, however, when it is desired that the approach to the center of the line should be more gradual, and consequently more exposures are needed, the series is continued on a second plate. In this way series of photographs of some special feature have been made in rapid succession with ten or twelve different settings from λ 3952.4 to λ 3968.6. The time between successive exposures is just long enough to run the telescope back to the original declination so as to drive the feature across the first slit again, to move the second slit to the desired setting, and to change its width as approach is made to the more intense part of the dark absorption band. The records with settings on the continuous spectrum at λ 3952, approximately midway between the H and K lines, show only faculæ at the limb with but very faint traces at the center of the disk. They are similar to direct photographs. These vague markings in the center gradually grow in strength until the setting is within the broad absorption band, at λ 3962.2, where the markings appear in the center of the disk sharply defined. Careful comparisons of the markings at this wave-length with the faculæ show the agreement in form, so far as they can be compared near the limb, to be perfect. No change in form is detected until the region of λ 3965.5 is reached. From this point on to λ 3968.6 the change in form and size and contrast is progressive, at first slow, then rapid.

There has been some discussion as to the point in the approach to H_2 where we may say the faculæ are no longer depicted and the calcium flocculi appear. Mr. Evershed's[1] view confines the influence of calcium to the central H_2 region, or within the limits where true reversal is found, and up to this point the forms are considered faculæ. If this view is correct, then, until the H_2 region is reached, there should be no such change in form of the markings as appears in a series of photographs like that described above. Moreover,

[1] *The Observatory*, **27**, 164, 1904.

PLATE XVII

set at

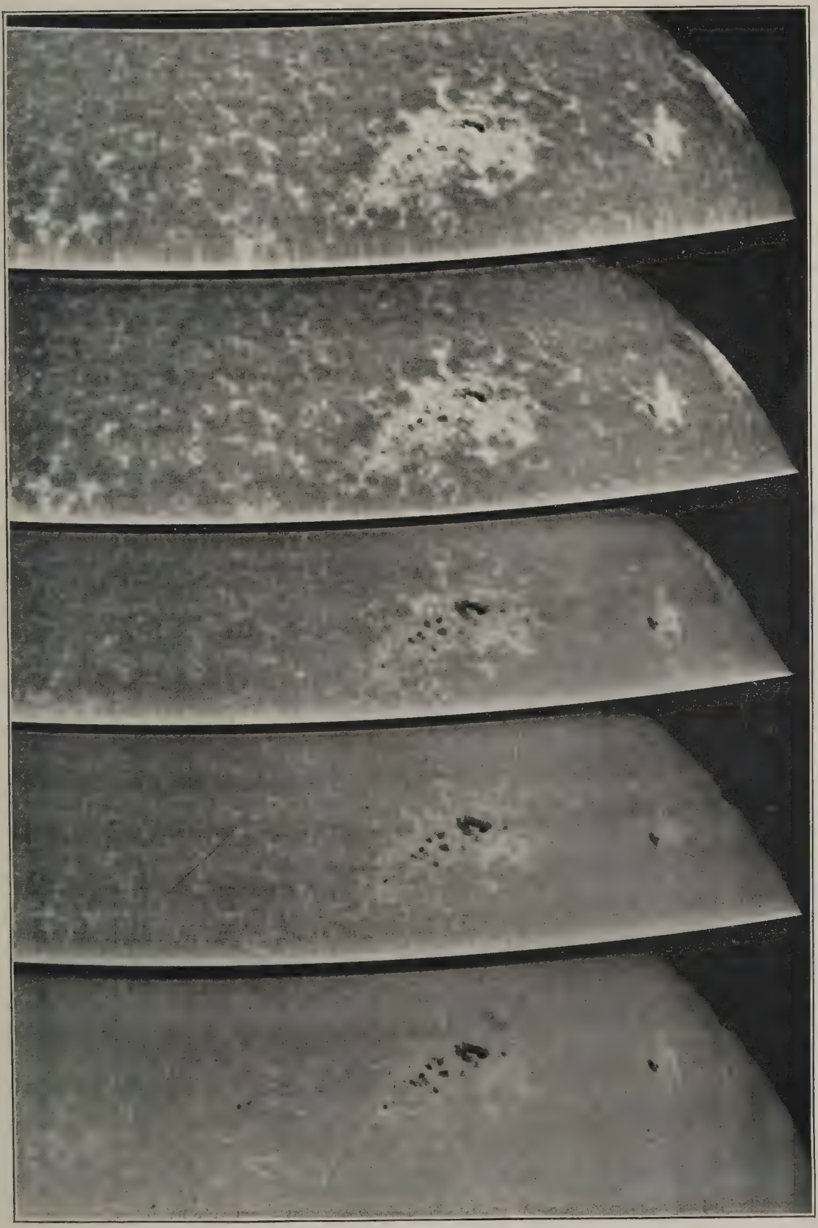
3968.6

3968.2

3967.8

3966.4

3965.0



Series obtained on August 25, 1904, with slit settings approaching the center of the H line. Order: from lowest upwards.

the contrast should not increase with near approach to the H_2 region, for the continuous spectrum of the faculæ noticeably diminishes in intensity.

In the working hypothesis adopted by Messrs. Hale and Ellerman, the appearance of markings at the center of the disk at λ 3962.2 was considered as evidence that the calcium vapor, mixed with the general mass of condensed vapors in the faculæ had been differentiated, and its radiation alone was recorded. The agreement of the form of the markings, which they called flocculi, with the faculæ was accounted for by the intimacy of the mixture at this low level. This view may ultimately be found to be unreservedly tenable, but it would seem that the change in form of the flocculi should be progressive from this point, if we are dealing with calcium alone. As a matter of fact, pointed out above, the changes do not begin until the region λ 3965.5 is reached. It may be that this region should be considered the bounding zone of the supremacy of calcium. Two reasons, one of which has just been implied, might indicate this. It marks the change of the markings from the facular form, and from the study of the spectrum it seems to be roughly the point where the decrease begins in the intensity of the continuous spectrum of the faculæ.[1] However, a more extensive collection of plates bearing on this subject, taken at times of the very best seeing, is needed for study on this point. The taking of these occupies no unimportant place in the program of the current year. Further reference will be made to this discussion later.

Plate XVII shows a series of exposures upon a large spot-group. The settings are at λ 3965.0, λ 3966.4, λ 3967.8, λ3968.2, and λ 3968.6, and were made at the following times in the morning of August 25, 1904, $9^h\,0^m$, $9^h\,10^m$, $9^h\,12^m$, $9^h\,13^m$, and $9^h\,14^m$ C. S. T. The progressive change in form, size, and contrast is clearly brought out. Another fact clearly shown is that few if any flocculi appear in the high levels whose roots, generally in miniature, are not seen in the low levels. Even the especially brilliant points which Messrs.

[1] See also the *Astrophysical Journal* for April (21, 264, 1905), where Professor Hale says: "The continuous spectrum of the faculæ is usually weakened by absorption over more than half the width of the H_1 and K_1 bands," and shows Plate XIV as evidence.

Hale and Ellerman called "eruptions" can be traced, as such, to λ 3967. In rare cases they may be followed even farther.

Hydrogen flocculi plates, which were obtained using the lines H_β, H_γ, and H_δ, in many cases show eruptions coincident with those of calcium. The excessive energy implied by these brilliant points in the flocculi is further indicated by the presence of associated prominences. In nearly all cases where these eruptions could be traced to the limb, the prominence plate revealed a prominence hovering over the flocculus. There are cases where the actual eruptive feature is seen projecting beyond the limb.

The work on the hydrogen flocculi with increased dispersion brought out few new points, but was rich in suggestions. Spectroheliograms, using the three lines mentioned above, give forms which are practically identical. Work is being continued on these lines.

The program of observations on lines other than H and K, using increased dispersion, included iron lines at λ 4045.975 and λ 4383.720, calcium at λ 4226.904, strontium at λ 4077.885, scandium at λ 4320.907, and chromium at λ 4254.505 and λ 4274.958. There is difficulty in setting on some of these lines, but in many cases spectroheliograms were obtained showing detail in the center of the disk. It is a noteworthy fact that the markings near the limb differ in no wise from the faculæ, nor in the center of the disk from the forms obtained with setting at λ 3962.2. This failure to detect a change in form may be due to one of two reasons. Perhaps the appearance of markings in the center of the disk is not indicative that we have differentiated the radiation of the element in question; but that the absorption of the general radiation of the photosphere, as we enter the shading of a line, brings out the faculæ. In dealing with a narrow line, the dispersion used may be insufficient to make the line completely fill the second slit, and therefore the radiation in question cannot be segregated to the exclusion of that of the faculæ. Or if we accept the opposite view of Messrs. Hale and Ellerman, and take the appearance of markings in the center of the disk as evidence that the element is manifesting itself, we may conclude that the dispersion is insufficient to bring out the high-level phases in the distribution of the element, or else that it does not rise to sufficient height to assume forms materially different from the

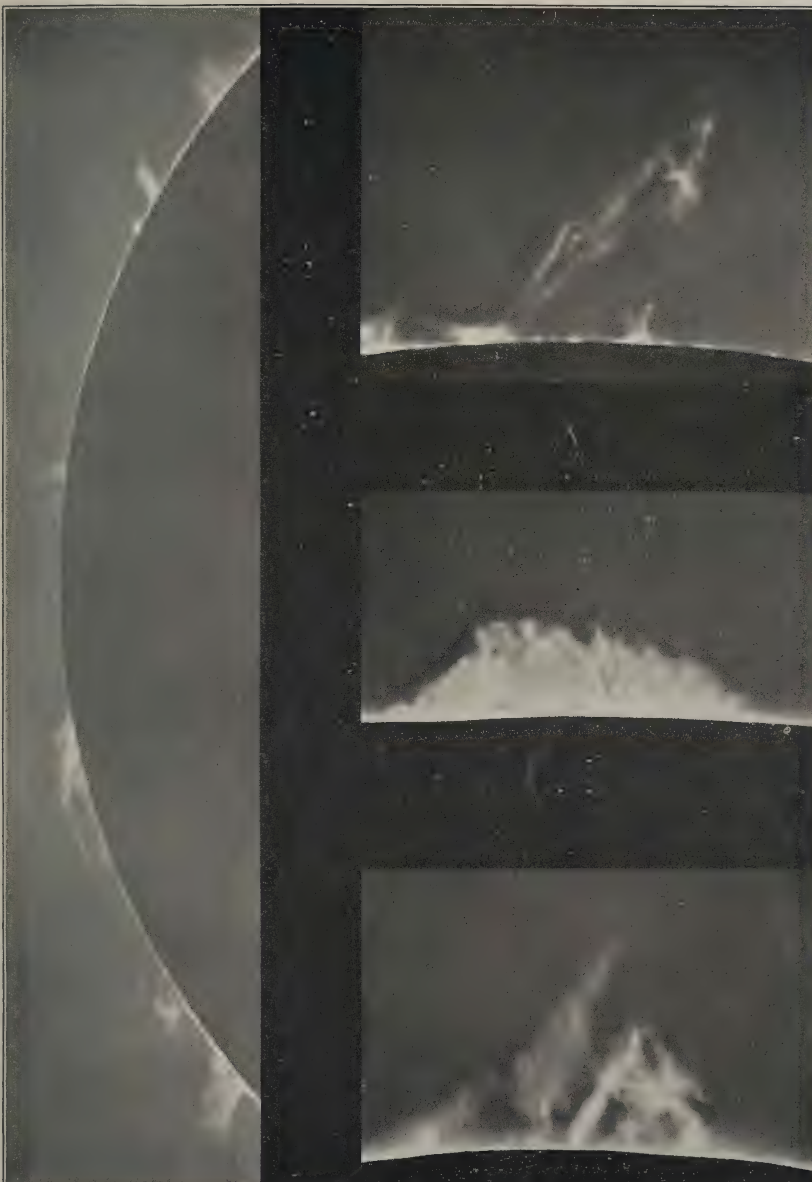
PLATE XVIII

2

1

3

4



1. Prominences on W. limb, November 3, 1904. Natural size.
2. July 20, 1904. 3. October 3, 1904. 4. August 26, 1904. Twofold enlargements. Scale for 2, 3, and 4: 78,000 km per cm.

faculæ. Observations of Lockyer,[1] Frost,[2] and Mitchell[3] on the height which these elements reach as shown in flash spectra obtained at solar eclipses indicate low altitudes as compared to hydrogen and calcium. Very delicate setting indeed would seem to be necessary to show changes in distribution of any of these elements at different levels. It is hoped that the high dispersion which Mr. Hale is providing in the spectroheliograph at the Solar Observatory of the Carnegie Institution on Mount Wilson will be able to solve these points.

Plate XVIII shows the availability of the Rumford spectroheliograph for the photography of prominences. The year was not prolific in prominences, and no extraordinary ones were observed. Fig. 1 shows prominences obtained at 1:45 P. M. on November 3, 1904. None of the prominences are high or of unusual form, but there were few plates which showed such a wealth of them. The prominences numbered 2, 3, and 4 were photographed on July 20, 9:37 A. M.; October 3, 10:35 A. M.; and August 26, 10:01 A. M., respectively.

In closing, I wish to express my indebtedness to Mr. J. A. Brown, who as a volunteer research assistant devoted a summer to helping in these observations.

YERKES OBSERVATORY,
February 24, 1905.

[1] *Recent and Coming Eclipses*, p. 202.

[2] *Astrophysical Journal*, **12**, 307, 1900. [3] *Ibid.*, **15**, 119, 1902.

ON THE SPECTRA OF THE ALKALINE-EARTH FLUORIDES IN THE ELECTRIC ARC

By CH. FABRY

Most salts when placed in the electric arc give no spectrum other than that of the corresponding metal. I have discovered that the case is different for the fluorides of calcium, strontium, and barium. In analyzing the light of an electric arc taken between hollow carbons containing one of these salts we obtain, in addition to the spectrum of the metal, a very brilliant band spectrum, characteristic of the salt employed. We must thus admit the existence of vapors of these fluorides, incompletely dissociated, at the temperature of the electric arc. These spectra, which present interesting peculiarities, have seemed to me worthy of a careful investigation.

The wave-lengths have been measured, by comparison with iron lines, with the aid of a prism spectroscope recently described by M. Jobin and myself.[1] The precision of the settings is such as to permit the wave-lengths of the fine lines to be calculated to within about one part in one hundred thousand. The wave-lengths of Kayser and Runge were adopted for the iron lines.[2] The observations were wholly visual; the ultra-violet region of the three spectra was explored by photography, using a Rowland grating, without encountering a single band due to the fluorides.

I may be permitted to recall at the outset certain well-known results relating to band spectra; this is the more necessary in view of the fact that, in certain instances, the adopted terminology is not completely fixed, and consequently misunderstandings arise between different observers.

A *band* is composed in general of a large number of lines, regularly distributed in the spectrum, starting from a line which is the most brilliant of the group, and which is called the *head* of the band. Starting from the head, the intensities of the successive lines continue to decrease, while the intervals between the successive lines

[1] *Journal de Physique,* (4) **3,** 202, 1904.

[2] *Abhandlungen der K. Akad. d. Wiss.,* Berlin, 1888.

increase; we thus have a series of lines of decreasing intensity which are more and more widely separated. If each line be represented by the *frequency* of the vibratory motion, or, what amounts to the same thing, by the reciprocal of the wave-length, we find that the intervals between the successive lines increase in arithmetical progression (Deslandres).[1] It amounts to the same thing to say that the frequency N of the line numbered m, starting from the head, may be expressed by an integral function of the second degree in m. In a spectroscope of small dispersion, since the lines are not separated, the appearance is that of a continuous band, sharply bounded at the *head*, whose intensity gradually decreases in the direction in which the lines extend outward from the head. The band is said to fall off toward the red or toward the violet, according to the direction in which the lines which compose the band extend outward from the head.

Ordinarily a band does not occur alone; there are several, of similar character, which usually encroach upon one another, the whole forming a *series of bands*. In this series it is especially important to consider the positions of the various heads; these, considered alone, and sharply measurable only when the dispersion is small, form a *series of heads*.

Having recalled these facts, let us return to the spectra of the fluorides, and let us consider in particular that of the fluoride of calcium, which is the easiest to obtain.[2]

Fig. 1 represents the various parts of this spectrum. Each of the strokes in the drawing is in reality a very bright line, sharply bounded on one side, and prolonged on the other side by a diffuse light, which grows fainter as the distance from the bright part increases. The appearance is exactly that of a *band* in a spectroscope of small

[1] I here pass over without mention a great number of interesting details which may be found set forth in the memoirs of M. Deslandres.

[2] There may be found in commerce, under various names (carbons for flame arcs, metallized carbons, etc.), carbons for arc lamps which contain calcium fluoride. The arc taken between these carbons is very brilliant, and gives a very bright spectrum of calcium fluoride. Some of these carbons also contain barium, and give also the spectrum of barium fluoride. The spectrum of calcium fluoride constitutes a very sensitive reaction of the fluorides: it is only necessary to impregnate carbons free from fluorides with a salt of calcium; the addition of a trace of any fluoride causes the bands of $CaFl_2$ to appear in the spectrum of the arc, particularly the green group B, which is the most brilliant.

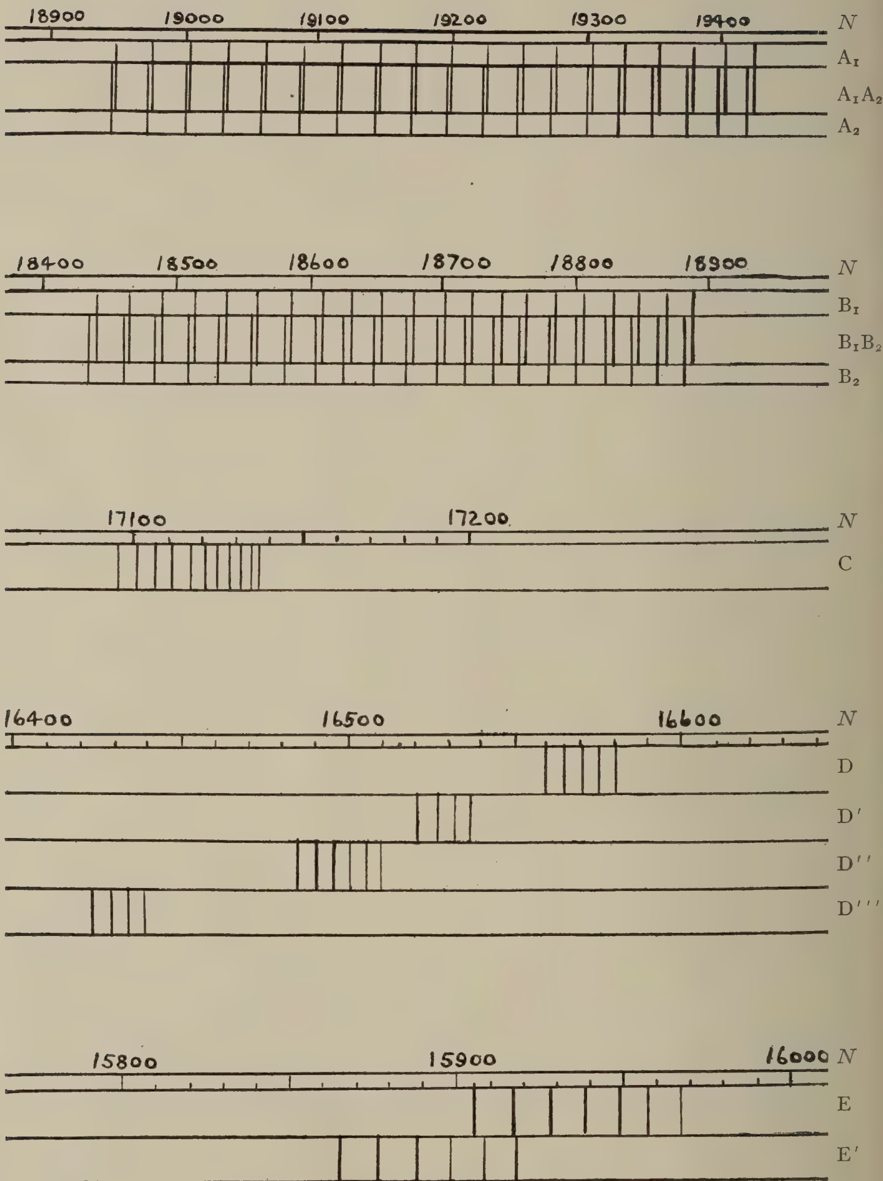


FIG. 1.—Spectrum of Fluoride of Calcium

dispersion; the bright part, sharply bounded on one side, corresponds to the head of such a band. A careful examination shows that this is precisely the interpretation of the observed appearance; the lines which constitute each band are so close together that in the neighborhood of the head I have not been able to separate them, even with the aid of a large concave Rowland grating of 7 meters radius.[1] At some distance from the head the less closely spaced lines commence to separate, but they then begin to encroach upon the lines of the neighboring heads, and measurement becomes impossible.

To sum up, each of the lines I have measured is, in reality, a *head of a band*, and the groups shown in the drawing are series of heads. These spectra cannot be used to increase our knowledge of the distribution of lines in a single band, since the lines are not separately measurable; on the other hand, their study will give us valuable information on the distribution of heads in a series, since these heads are numerous and well defined.

The various series may be divided, at a first glance, into two categories:

1. Those which are designated on the drawing by the letters A and B. From each head there extends a band falling off toward the red. The series of heads commences abruptly with the brightest head, and the others, beginning with that one, extend toward the red; the distances between the successive heads continue to increase, though slowly, in the same direction.

2. Those which are designated by C, D, and E. The corresponding bands fall off toward the violet. The series of heads also commences abruptly with the brightest head, and the following ones extend toward the violet; but the intervals between the successive heads continue to decrease.

The two kinds of series obey the following law:

If each head is represented by its *frequency* N,[2] we find that the intervals between the successive heads form an arithmetical progression; they follow the same law that ordinarily holds for the lines

[1] The defining power of this apparatus is, however, not much greater than that of my spectroscope, and it gives less brilliant spectra.

[2] N is, in reality, a nearly constant factor, the reciprocal of the wave-length *in vacuo*. We have taken for N the number of wave-lengths contained in one centimeter.

belonging to a single head, and which form a band. M. Deslandres long ago announced this law of the distribution of heads; in the present case, it is verified with a precision equal to that of the observations, in series where more than twenty heads of bands may be measured.

If, then, the heads of a certain series are numbered, the frequency N of the head numbered m will be expressed by a second degree function of m, whatever be the origin and the direction of the numbering.

There is, nevertheless, a great difference between the distribution of lines in a band and that of heads in a series. In the first case, the intensity of the lines always decreases as the interval between the lines successively augments, starting from the head of the band where this interval is very small. The same thing does not hold in the series of heads: if we take a series of the second class, the intensities continue to decrease in proportion as the intervals diminish. In a series of the first class the intensities decrease in proportion as the intervals increase, but from the first head, which is the brightest, the interval is already great, and it increases but slowly. In order to have an analogous distribution of the lines in a band, it would be necessary to imagine that a considerable number of lines in the neighborhood of the head have completely disappeared.

We now come to the numerical expression of the various series. The frequency N of the head m may be expressed by an equation of the form $N=A-(Bm+C)^2$. The value of the coefficients B and C depends on the origin and direction of the numbering. As the series always extends only on one side from the brightest head, the most natural way of numbering has seemed to me the following:

Give to the brightest head the number 0, and to the following ones 1, 2, 3, etc. In this way m will have only positive values, and the intensities will always decrease as the order numbers increase. For the series of the first class, the intervals between the successive heads increase with m, and B is positive. It is negative for the series of the second class (the constant, C, being always considered positive).[1]

[1] In my first studies of the spectra of fluorides (*Comptes Rendus*, **138**, 1581, June 20, 1904) I chose a numbering such that the constant C was zero, and the equation took the form $N=A-bm^2$. The initial head (the most brilliant of the series) then had a certain number m_0, and the following ones had numbers starting from m_0, in the increasing or decreasing direction, according to circumstances. I have since adopted the system of numbering just described, which is more natural and which leads to interesting relations between the numerical coefficients.

The spectrum of strontium fluoride offers striking analogies with that of the calcium salt.

The following table gives the equations of the various series of the two spectra. The corresponding series are represented by the same letters. All the values of N are reciprocals of the wave-lengths *in vacuo.*

TABLE I

EQUATIONS OF THE SERIES OF HEADS OF THE BANDS IN THE SPECTRA OF THE FLUORIDES OF CALCIUM AND STRONTIUM. $N=A-(Bm+C)^2$.

(The intensities in each series decrease as the order number increases.)

$Ca\ Fl_2$				$Sr\ Fl_2$			
Series	A	B	C	Series	A	B	C
A_1......	20458.9	+0.3776	32.10	A_1......	18813.1	+0.1835	32.10
A_2......	20455.2	+0.3768	32.10	A_2......	18800.8	+0.1874	32.10
B_1......	19925.1	+0.3209	32.10	B_1......	18350.5	+0.135	32.10
B_2......	19918.9	+0.31895	32.10	B_2......	18327.6	+0.128	32.10
C.......	17146.1	−0.420	7.15				
D.......	16609.3	−0.417	7.07	D.......	15902.8	−0.250	7.07
D′......	16570.8	−0.400	7.07	D′......	15622.5	−0.250	7.07
D″......	16534.4	−0.404	7.07				
D‴.....	16473.0	−0.383	7.07				
E.......	16046.2	−0.50	11.9	E.......	15492.7	−0.34	11.9
E′......	16006.5	−0.50	11.9	E′......	15455.9	−0.35	11.9
				E″......	15161.4	−0.35	11.9
				E‴.....	15214.1	−0.33	11.9

The comparison of these numbers leads to the following results:

1. If we consider the corresponding series of the two fluorides, the constant A is always greater in the case of calcium than in that of strontium; in other words, the series are displaced toward greater wave-lengths when the atomic weight of the metal increases. It is well known that the same fact holds true for the lines of metals.

2. The constant C has the same value for the corresponding series of the two salts. It is impossible to say whether there is an exact equality or only a partial one, since for certain series, where the number of measurable elements is small, the constants are not very well determined. Formulæ might be given involving a slight change in the constant B and a corresponding small change in C, which would nevertheless represent the observations equally well. However, for certain series (A and B of calcium, A of strontium)

the coefficients are very well determined and the equality of the constant C is certainly true within a few hundredths of its value.

3. The constant B decreases in passing, in a corresponding series, from calcium to strontium; in the latter case the lines are consequently closer together.

It is interesting to seek for analogies between the spectra which I have just described, and the band spectra previously known. The arrangement of heads which is found in the series of the second class exists in a certain number of known spectra; for example, in the beautiful bands of cyanogen. As for the structure of the series of the first class (Series A and B), it recalls the absorption spectrum of oxygen, if the complicated part which occurs near the beginning of each group is left out of account. May this peculiar absorption spectrum be formed, in reality, not of simple bands, but of a series of heads of bands?

Barium fluoride also gives a magnificent spectrum of bands, of which only the heads are measurable; these form series of heads, as in the case of the two other fluorides. All of these series belong to the second class, i. e., the intensities of the heads diminish as the intervals between them diminish. These series are not analogous to those of the two other fluorides; they are turned in the opposite direction to the series of the second class of the fluorides of calcium and strontium. The bands which extend out from the heads fall off toward the red, and it is also in the direction of the red that the intervals between the heads increase, while their intensities decrease. The formulæ of these series are consequently of the form $N=A+(Bm+C)^2$. These bands occur in the blue; the analogues of those in the spectra of the two other fluorides should occur toward the greater wave-lengths; perhaps they are in the infra-red.

The following table gives the formulæ of the various series of barium fluoride:

TABLE II

Equations of the Series of Heads of Bands in the Spectrum of Barium Fluoride. $N=A+(Bm+C)^2$

Series	A	B	C
1	20111.0	−0.4302	9.034
2	20197.8	−0.441	7.06
3	19842.7	−0.4362	13.522
4	19711.7	−0.35765	16.715
5	19416.2	−0.3932	10.618
6	19531.9	−0.479	7.19

TABLE III

$CaFl_2$

Series A_1			Series A_2		
m	*N* obs.	*N* calc.	*m*	*N* obs.	*N* calc.
0..........	19428.5	19428.5	0.........	19424.8	19424.8
1..........	403.7	404.0	1.........	400.0	400.4
2..........	379.8	379.5	2.........	375.9	375.8
3..........	354.4	354.5	3.........	351.0	351.0
4..........	329.4	329.3	4.........	326.3	325.8
5..........	303.7	303.7	5.........	300.3	300.3
6..........	278.0	277.9	6.........	275.1	274.5
7..........	252.1	251.9	7.........	248.5	248.4
8..........	225.6	225.4	8.........	222.6	222.2
9..........	198.6	198.9	9.........	196.0	195.6
10..........	172.0	171.9	10.........	169.3	168.7
11..........	144.5	144.5	11.........	141.4	141.3
12..........	117.5	117.1	12.........	114.8	114.1
13..........	089.0	089.3	13.........	085.2	086.3
14..........	060.4	060.3	14.........	057.4	057.3
15..........	032.2	032.8	15.........	029.7	030.0
16..........	.....	.....	16.........	....	.....
17..........	.....	.....	17.........	.....	.....
18..........	18946.2	18945.9	18.........	18942.9	18943.3

Series B_1			Series B_2		
m	*N* obs.	*N* calc.	*m*	*N* obs.	*N* calc.
0..........	18894.9	18894.7	0.........	18888.1	18888.5
1..........	873.9	874.0	1.........	867 7	867.9
2..........	853.0	853.0	2.........	847.3	847.1
3..........	831.8	831.9	3.........	826.5	826.2
4.	811.0	810.5	4.........	805.1	805.0
5..........	789.5	789.1	5.........	783.5	783.5
6..........	767.2	767.4	6.........	761.9	761.9
7..........	745.2	745.5	7.........	740.2	740.1
8..........	723.1	723.3	8.........	718.6	718.1
9.	701.0	700.9	9.........	696.3	695.9
10..........	678.2	678.4	10.........	673.4	673.6
11..........	655.4	655.6	11.........	651.0	651.0
12..........	632.1	632.6	12.........	627.6	628.2
13..........	609.8	609.4	13.........	605.2	605.2
14..........	586.5	586.1	14.........	581.7	581.9
15..........	561.9	562.5	15.........	559.0	558.5
16..........	539.0	538.8	16.........	535.1	534.8
17..........	515.1	514.7	17.........	511.2	511.0
18..........	490.6	490.6	18.........	486.6	487.0
19..........	465.5	466.1	19.........	461.7	462.7
20..........	441.8	441.5	20.........	438.0	438.3

TABLE III—*Continued*

Series C			Series C		
m	N obs.	N calc.	m	N obs.	N calc.
0	17094.8	17095.0	6	17124.6	17124.7
1	100.6	100.8	7	128.3	128.4
2	106.4	106.3	8	131.7	131.7
3	112.2	111.4	9	134.6	134.7
4	116.5	116.2	10	137.3	137.4
5	120.8	120.6			

Series D			Series D′		
m	N obs.	N calc.	m	N obs.	N calc.
0	16559.2	16559.3	0	16520.8	16520.8
1	565.1	565.1	1	527.1	526.3
2	570.3	570.4	2	531.6	531.5
3	575.4	575.4	3	536.3	536.4
4	580.1	580.1			

Series D″			Series D‴		
m	N obs.	N calc.	m	N obs.	N calc.
0	16484.3	16484.4	0	16423.0	16423.0
1	490.0	489.9	1	428.4	428.3
2	495.1	495.2	2	433.2	433.3
3	500.2	500.0	3	438.0	438.0
4	504.8	504.7			
5	508.8	508.9			

Series E			Series E′		
m	N obs.	N calc.	m	N obs.	N calc.
0	15904.6	15904.6	0	15865.2	15864.9
1	916.3	916.2	1	876.3	876.5
2	927.0	927.4	2	887.4	887.7
3	938.3	938.0	3	898.5	898.3
4	948.3	948.2	4	907.6	908.5
5	958.0	957.8	5	918.4	918.1
6	967.0	967.0			

TABLE III—*Continued*

Sr Fl₂

Series A_1			Series A_2		
m	*N* obs.	*N* calc.	*m*	*N* obs.	*N* calc.
0	17782.9	17782.7	0	17770.3	17770.4
1	770.3	770.9	1	.....	.....
2	757.9	759.0	2	.....	.....
3	746.6	747.1	3	.....	.....
4	734.3	735.0	4	.....	.....
5	723.3	723.1	5	.....	.....
6	711.0	710.8	6	17697.3	17696.9
7	698.6	698.6	7	684.8	684.4
8	686.6	686.3	8	672.2	671.9
9	674.2	674.0	9	659.3	659.2
10	661.8	661.5	10	646.5	646.5
11	650.0	649.1	11	634.2	633.8
12	636.6	636.5	12	619.4	621.0
13	623.9	623.9	13	607.3	607.9
14	612.0	611.2	14	595.6	595.1
15	598.8	598.4	15	580.8	582.0
16	585.7	585.6	16	568.8	568.9
17	572.9	572.7	17	554.1	555.7
18	559.7	559.7	18	541.2	542.3
19	545.9	546.7	19	528.4	529.1
20	533.9	533.6	20	516.5	515.7
21	520.3	520.5	21	502.2	502.3
22	507.3	507.2	22	489.8	488.7
23	494.5	494.0	23	476.0	475.1
24	480.4	480.5	24	461.3	461.4
25	467.0	467.1	25	448.4	447.6
26	453.9	453.6			

Series B_1			Series B_2		
m	*N* obs.	*N* calc.	*m*	*N* obs.	*N* calc.
0	17320.1	17320.1	0	17297.2	17297.2
1	311.2	311.5	1	289.0	289.0
2	302.8	302.7	2	280.9	280.7
3	293.6	293.9	3	272.2	272.4
4	284.6	285.1	4	264.6	264.1
5	276.5	276.3	5	255.7	255.7
			6	247.6	247.3
			7	239.1	238.9
			8	230.4	230.4
			9	222.0	221.9
			10	212.7	213.4
			11	203.9	205.2

TABLE III—*Continued*

Series D			Series D′		
m	*N* obs.	*N* calc.	*m*	*N* obs.	*N* calc.
0	15852.8	15852.8	0	15573.0	15572.5
1	856.0	856.3	1	576.2	776.0
2	859.6	859.6	2	578.5	579.3
3	862.9	862.9			
4	866.1	866.0			
5	868.9	868.9			
6	871.8	871.8			
7	874.5	874.5			
8	877.6	877.1			

Series E			Series E′		
m	*N* obs.	*N* calc.	*m*	*N* obs.	*N* calc.
0	15351.1	15351.1	0	15314.3	15314.3
1	358.4	359.1	1	322.6	322.5
2	366.4	366.8	3	330.3	330.5
3	374.3	374.3	3	338.0	338.2
4	383.2	381.6	4	346.9	345.7

Series E″			Series E‴		
m	*N* obs.	*N* calc.	*m*	*N* obs.	*N* calc.
0	15019.8	15019.8	0	15072.4	15072.5
1	027.8	028.0	1	080.1	080.2
2	035.8	036.0	2	087.6	087.8
3	043.9	043.7	3	094.6	095.1
4	051.4	051.2	4	102.1	102.2
			5	110.4	109.0
			6	116.4	115.7

TABLE III—*Continued*

$BaFl_2$

SERIES 1

m	*N* obs.	*N* calc.
0	20192.6	20192.6
1	185.1	185.0
2	177.7	177.8
3	170.9	170.9
4	165.0	164.5
5	158.3	158.4
6	152.5	152.6
7	147.3	147.3
8	142.3	142.3
9	137.7	137.6
10	133.5	133.4
11	129.5	129.5

SERIES 2

m	*N* obs.	*N* calc.
0	20247.6	20247.6
1	241.1	241.6
2	235.9	235.9
3	231.1	230.7
4	225.8	225.8

Series 3

m	*N* obs.	*N* calc.
0	20025.3	20025.6
1	014.3	014.0
2	003.1	002.7
3	19991.7	19991.9
4	981.2	981.4
5	970.9	971.3
6	961.7	961.6
7	952.2	952.3
8	943.1	943.3

SERIES 4

m	*N* obs.	*N* calc.
0	19991.7	19991.1
1	979.2	979.2
2	967.4	967.7
3	956.0	955.7
4	945.1	945.3
5	934.3	934.5
6	923.9	923.9
7	913.7	913.6
8	903.2	903.6
9	893.6	893.8
10	884.1	884.3
11	875.0	875.0
12	866.4	866.0
13	857.2	857.2
14	848.8	848.8
15	840.1	840.5
16	832.8	832.5
17	825.3	824.8
18	817.7	817.3
19	810.4	810.1
20	802.9	803.1
21	797.1	796.4
22	789.6	790.0
23	783.9	783.8

SERIES 5

m	*N* obs.	*N* calc.
0	19529.2	19528.9
1	520.7	520.7
2	513.1	512.9
3	505.6	505.3
4	498.7	498.0
5	491.3	491.0
6	484.5	484.4
7	478.4	478.1
8	471.7	472.0
9	466.2	466.3
10	460.9	460.9
11	455.6	455.8
12	451.1	451.0
13	446.3	446.5
14	442.6	442.3

Series 6

m	*N* obs.	*N* calc.
0	19583.6	19583.6
1	577.1	576.9
2	570.7	570.7
3	565.1	565.0
4	559.7	559.7

THE "OPTICAL POWER" OF THE ATMOSPHERE AND ITS MEASUREMENT

By KARL EXNER and W. VILLIGER

In the *Vierteljahrsschrift der Astronomischen Gesellschaft* (**37**, 3, 1902) and in the *Monthly Notices of the Royal Astronomical Society* (**53**, 40, 42, 337, 1902) Percival Lowell published communications entitled "A Standard Scale for Telescopic Observations" and "Expedition for Ascertaining the Best Location of Observatories." In these articles it is stated that the quality of the atmosphere for astronomical observations on different places on the Earth's surface is judged according to the appearance which the fixed stars in that place show in a telescope of fairly large aperture. A scale of six gradations was also made for this appearance of the stars.

In this connection it is to be noted that in the year 1887 this same idea was expressed by one of ourselves, and it was shown that it was possible not only to estimate the quality of the atmosphere, but also to measure it numerically.[1]

The action of the tremulous currents in the air is the same in observing the fixed stars through instruments of large aperture as if the eyepiece were inaccurately focused, and it cannot be remedied. We may, therefore, as in Foucault's definition of the optical power of an instrument, designate the reciprocal of the average horizontal diameter of the star's disk, estimated in seconds, at the given place as the "optical power" of the atmosphere at this place $\left(O.\,P. = \frac{1}{\text{diameter}}\right)$. This consideration gave occasion for certain quantitative studies for the measurement of Newton's phenomenon (conversion of the point image of a star into a bright surface by irregular deviation in the atmosphere), which measurements were made principally in the years 1901 and 1902 at the Royal Observatory at Munich with the $10\frac{1}{2}$-inch refractor. On making nearly three hundred measures of D (D being the horizontal diameter of a star's disk), it appeared:

[1] *Astronomische Nachrichten*, **116**, 321, 1887.

1. D increases with ζ (true zenith distance).[1]

2. Stars of unequal magnitude, under otherwise similar circumstances, show approximately equal values of D.

3. The tremor (pendulum motion) of a fixed star, with sufficiently reduced aperture of a large instrument, agrees, as far as can be seen, with the diameter D of the star when observed with a full-aperture instrument.

Noticing now that the D of a star depends on the zenith distance, it is suggested that the measurements for the determination of the optical power should be made at limited zenith distances, perhaps at true zenith distances $\zeta = 70°$ to $80°$. If the method of the D-determinations is to be applied further for the determination of the optical power of a place, it is desirable to choose stars of nearly similar magnitude, as stars of the third to the sixth magnitude.

When this method of determining the diameter was applied in Munich for determining the optical power of the atmosphere at the Royal Observatory, the result in the first approximation was: $O.\ P. = \frac{1}{3}$. The details of this are given elsewhere.[2] The result $O.\ P. = \frac{1}{3}$ shows therefore that for the location of the observatory at Munich stars of the third to the sixth magnitude at 70°–80° true zenith distance show a horizontal diameter of $3''$. A more detailed discussion[3] of the observations of scintillation at Munich indicates a distinct dependence of the D-value on the brightness of the star. At the zenith distance $\zeta = 0°$ to $50°$, the diameters of the stars measured are greater as the brightness diminishes; while in the neighborhood of the horizon, $\zeta = 60°$ to $90°$, an increase of the tremor disk is noticeable with the growing brightness of the star. The explanation of this phenomenon is carried further in the place cited. Taking account of this dependence, we have the reduction to magnitude 6.0, and zenith distance, $\zeta = 75°$, in accordance with the approximate value:

$$O.\ P.,\ \text{Munich} = \frac{1}{2.7}, \qquad \left\{ \begin{array}{l} m = 6.0 \\ \zeta = 75°. \end{array} \right.$$

[1] This principle was first expressed by E. R. von Oppolzer.

[2] Karl Exner and W. Villiger, "Ueber das Newton'sche Phänomen der Scintillation," *Sitzb. der kais. Akad. d. Wissensch. in Wien.*, Math.-naturw. Klasse; **111**, II*a*, 1902; and **113**, II*a*, 1904.

[3] Wiener, *Sitzungsberichte*, **113**, 1026–1037, 1904.

The determination of the optical power of an observatory can be made with very little trouble. In order to get an approximate value, it is sufficient to take four diameter measurements in the cardinal directions once each month of the year for stars of the third to the sixth magnitude at 70° to 80° true zenith distance, with an instrument of sufficiently large aperture.

The idea of optical power can also be used in a broader sense. When, for example, Secchi separated double stars of $\frac{1}{2}''$ distance in the most quiet atmosphere under the favorable conditions of Rome, while in disturbed atmosphere the diameters of the brighter stars could reach $8''$; so it can be said that at a given place, at a given time and in a given direction, the optical power of the atmosphere in the first case is greater than 2, and in the second place $\frac{1}{8}$. When, further, Montigny found the greatest amplitude of the tremor of a distant object was $25''$ during the day, the optical power of the intervening layer of air was $\frac{1}{50}$. Finally, when the amplitude of the tremor of the fixed stars was found by Douglas and See at the Lowell Observatory to be roughly $0''.5$ to $2''.0$, the optical power of the atmosphere would be $O.\ P. = 1$ to $\frac{1}{4}$.

A LIST OF TWELVE STARS WHOSE RADIAL VELOCITIES VARY

By W. H. WRIGHT

The variable radial velocities of the stars on the following list have been detected while following the regular program of the D. O. Mills Expedition from the Lick Observatory, University of California, to the Southern Hemisphere. These are in addition to the five cases of variability already announced in *Lick Observatory Bulletin* No. 60.

The custom adopted at Mount Hamilton of giving values of velocities depending on approximate measurements and reductions to the nearest kilometer is followed in this paper. An exception to the general rule of giving the results of careful measurements to the nearest tenth of a kilometer is made in the case of κ *Velorum* on account of the small number of lines in its spectrum and their slightly hazy character.

Most of these determinations have been made with λ 4341 ($H\gamma$) central in the camera, using an iron comparison spectrum. A number of spectrograms have, however, been secured with λ 4450 central, using titanium for comparison purposes. These plates appear to have a systematic error of about -1.1 km (observed value—true value). Velocity determinations from such spectrograms are indicated by an asterisk (*). Values depending on poor plates are indicated by a dagger (†).

α *Phoenicis* ($\alpha = 0^h\ 21^m\!.3$; $\delta = -42^\circ\ 51'$)

Date	Velocity	Measured by
1903, September 15	+80.7 km	R. H. Curtiss
October 1	+79.0	Palmer
October 5	+79.8	R. H. Curtiss
1904, August 3	+75.2	Wright
September 10	+74.4*	Palmer

γ *Phoenicis* ($\alpha = 1^h\ 24^m.0$; $\delta = -43°\ 50'$)

Date	Velocity	Measured by
1903, December 14..........	+40.6 km	Palmer
December 22..........	+36.4	Palmer
1904, June 22..............	+39.0†	Palmer
October 3............	+14.8*	Palmer
November 15..........	+33.0*	Palmer

The variable velocity of this star was detected by Dr. Palmer. The period as indicated by his observations appears to be roughly 190 days.

θ_1 *Eridani* ($\alpha = 2^h\ 54^m.5$; $\delta = -40°\ 42'$)

This star is the brighter component of the telescopic double θ *Eridani*. The spectrum is a composite one of the type of that of the brighter component of ζ *Ursae Majoris*. In fact, the system of θ *Eridani* may be said to be analogous to that of *Mizar*. On the first plate secured the $H\gamma$ line, which is broad, and a number of other lines, including λ 4481, all of a similar character, were observed to be double. The magnesium line λ 4481 is the only one which can be measured with any degree of satisfaction, and even in this case settings are subject to great uncertainty. The second spectrogram showed the components of the double lines closer together, while on the third the lines are apparently single. Only one spectrogram has been secured of θ_2 *Eridani*, the other component of the telescopic double. The lines on this plate are single.

Date	Velocity		Measured by
1904, December 23..........	−65±	+103±	Palmer
1905, January 2.............	−30±	+103±	Wright
January 9.............	+15±		Wright

X Eridani ($\alpha = 4^h\ 14^m.1$; $\delta = -34°\ 2'$)

This spectrum belongs to the same class as that of θ_1 *Eridani;* that is, both of the spectra are in evidence, though in this case the lines are quite narrow. The line λ 4481 is the only one on which measurements have been made.

Date	Velocity	Measured by
1903, October 3	+19± 1 km	Wright
1904, November 10	−13± +51±	Wright
December 7	+20±	Wright
December 14	−19± +70±	Palmer

δ Columbae $(\alpha=6^{h}\,18^{m}.4;\ \delta=-33^{\circ}\,23')$

Date	Velocity	Measured by
1903, December 5	−16.0 km	Palmer
1904, February 8	−12.7	Palmer
September 26	− 1.9*	Palmer
November 2	− 3.6*	Palmer
December 18	± 0.0	Palmer

The variable velocity of this star was detected by Dr. Palmer.

A Carinae $(\alpha=6^{h}\,47^{m}.6;\ \delta=-53^{\circ}\,31')$

Date	Velocity	Measured by
1904, November 17	+ 1.5 km*	Palmer
1905, January 9	+28	Wright
February 7	+48	Wright and Palmer

σ Puppis $(\alpha=7^{h}\,26^{m}.1;\ \delta=-43^{\circ}\,06')$

Date	Velocity	Measured by
1904, January 15	+86.8 km	Palmer
January 29	+89.0	R. H. Curtiss
October 25	+97.0*	Palmer
December 22	+103.4	Palmer

The variable velocity of this star was detected by Dr. Palmer.

a Puppis $(\alpha=7^{h}\,48^{m}.8;\ \delta=-40^{\circ}\,19')$

Date	Velocity	Measured by
1904, January 3	+26.5 km	Palmer
February 26	+28±†	Palmer
November 8	+17.2*	Palmer
December 10	+16.1*	Palmer
1905, February 23	+16	Wright

α Volantis ($\alpha = 9^h\ 0^m.9$; $\delta = -66°\ 0'$)

The spectra of the two components are present, and both contain numerous lines. On only one plate is the doubling of the lines complete; but the range in the degree of sharpness of the lines on the other plates affords ample confirmation of the composite nature of the star's spectrum.

Date	Velocity	Measured by
1903, December 14..........	+3 km (lines fairly sharp)	Wright
1904, February 11..........	+54± −54±	Wright
December 6...........	+4 (lines fairly sharp)	Palmer
December 24..........	+6 (lines fairly sharp)	Palmer
1905, January 15...........	+5 (lines rather hazy)	Wright
February 12..........	+8± (lines very hazy)	Palmer

a Carinae ($\alpha = 9^h\ 8^m.4$; $\delta = -58°\ 33'$)

Date	Velocity	Measured by
1904, February 29..........	+ 5.5 km	Wright
1905, January 30...........	+33.2	Palmer
February 9...........	+10.0	Wright and Palmer
February 22..........	+ 4.5	Palmer
March 7..............	− 1.2	Palmer

There is some evidence of a secondary spectrum. The $H\gamma$ line on the plate of January 30 has the appearance of a fairly narrow line displaced toward the red from the center of a rather broad absorption. It was, in fact, this peculiar appearance of the line that led me to suspect that the velocity of the star might prove variable.

κ Velorum ($\alpha = 9^h\ 19^m.0$; $\delta = -54°\ 35'$)

Date	Velocity	Measured by
1904, March 6..............	+67± km	Wright
1905, January 14...........	+13	Wright and Palmer
February 20..........	+63±	Wright
March 7..............	+53	Palmer

This star has fairly narrow hydrogen and helium lines. λ 4481 is also present and well defined. On account of the character of the star's spectrum, the values of the velocities are uncertain to the amount of a kilometer or two.

p Velorum ($\alpha = 10^{h}\,33^{m}.2$; $\delta = -47^{\circ}\,43'$)

This star has a composite spectrum similar to those described above, but is somewhat unique among stars of its class, from the fact that the lines, though numerous, are so sharp that settings can be made with great accuracy on the lines of both spectra.

Date	Velocity		Measured by
1903, December 14..........	+34 km		Wright
1904, February 6...........	?	+37	Wright
December 31..........	+22		Wright
1905, January 26...........	−10	+40	Wright and Palmer

In the cases where mention is made of the fact, the detection of variable velocity has been made by Dr. Palmer, in others by the writer. In the latter cases, the plate has frequently been turned over to Dr. Palmer for more deliberate measurement than the writer could afford the time to make.

Observatory of the D. O. Mills Expedition
to the Southern Hemisphere,
Santiago de Chile, March 9, 1905.

ON THE COMPUTATION OF THE MOON'S SPECTROGRAPHIC VELOCITY NEAR FULL MOON

By R. H. CURTISS

The determination of the Moon's spectrographic velocity from *American Ephemeris* data involves the use of the cosine of the angle (E) at the Earth's center between the Sun and Moon, and also the product $\sin E\frac{dE}{dt}$. E and the reciprocal of its rate of change, $\frac{dt}{dE}$, are regularly tabulated in the *Nautical Almanac* except for seven or eight days at full Moon, when our satellite is often most favorably situated for spectrographic observation. As a result, the facility of computation of the Moon's radial velocity is somewhat impaired, though the problem presents no difficulty. Cos E is computed directly and $\sin E\frac{dE}{dt}$ is obtained by numerical differentiation of $\cos E$, or more simply by means of differential formulæ.

A complete discussion of the five components of velocity to be considered in this case has been given by Professor Campbell.[1] Components V_3 and V_4 only are to be considered here and will be expressed invariably in kilometers per second. V_3 is the component of V_2 (the radial velocity of the Moon with reference to the Earth's center) in the line joining the Sun and Moon. V_4 is the component in this same line of the Moon's velocity normal to the radius vector drawn from the Moon to the Earth. The formulæ expressing these quantities are as follows:

$$V_3 = -V_2 \cos E \ ,$$

$$V_4 = [4.6856]\, D_2 \sin E \frac{dE}{dt} \ ,$$

where D_2 is the Moon's distance in kilometers from the Earth's center, and $\frac{dE}{dt}$ is expressed in seconds of arc per second of time.

Let A = the Sun's right ascension ,
α = the Moon's right ascension ,
D = the Sun's declination ,
δ = the Moon's declination .

[1] *Astrophysical Journal*, 11, 141, 1900.

The formulæ for the computation of $\cos E$ and $\sin E\frac{dE}{dt}$ are then:

$$\cos E=\sin\delta\sin D+\cos\delta\cos D\cos(A-\alpha)\ , \qquad (1)$$

$$\begin{aligned}\sin E\frac{dE}{dt}=&+\sin\delta\cos D\left[\cos(A-\alpha)\frac{d\delta}{dt}-\frac{dD}{dt}\right]\\ &+\cos\delta\sin D\left[\cos(A-\alpha)\frac{dD}{dt}-\frac{d\delta}{dt}\right]\\ &+\cos\delta\cos D\sin(A-\alpha)\frac{d(A-\alpha)}{dt}\end{aligned} \qquad (2)$$

First method.—This involves the computation of three values of $\cos E$, and a simple numerical differentiation. It is most convenient to compute $\sin E\frac{dE}{dt}$ in radians per hour by numerical differentiation of $\cos E$.

Then

$$V_3=-V_2\cos E\ ,$$
$$V_4=[6.4437]D_2\sin E\frac{dE}{dt}=278\times10^{-6}\times D_2\sin E\frac{dE}{dt}\ .$$

Example: Determine $\cos E$ and $\sin E\frac{dE}{dt}$, in radians per hour, for 1903, November 7d 19h 58m.

November 7	19h	20h	21h
A	222° 13′ 57″	222° 16′ 27″	222° 18′ 57″
D	−16 15 14	−16 15 59	−16 16 43
α	83 54 1	84 31 11	85 8 22
δ	18 16 14	18 17 01	18 17 41
$A-\alpha$	138 19 56	137 45 16	137 10 35
log sin δ	9.49624	9.49655	9.49680
sin D	9.44699$_n$	9.44732$_n$	9.44764$_n$
cos δ	9.97753	9.97750	9.97747
cos D	9.98228	9.98226	9.98223
cos $(A-\alpha)$	9.87333$_n$	9.86939$_n$	9.86537$_n$
cos δ cos D cos $(A-\alpha)$	9.83314$_n$	9.82915$_n$	9.82507$_n$
Add. log	0.05264	0.05317	0.05370
sin D sin δ	8.94323$_n$	8.94387$_n$	8.94444$_n$
Diff. log	0.88991	0.88528	0.88063
log cos E	9.88578$_n$	9.88232$_n$	9.87877$_n$
cos E	−0.76874	−0.76264	−0.75643
$\frac{d\cos E}{dt}=-\sin E\frac{dE}{dt}$	+0.00610		+0.00621
$\frac{d^2\cos E}{dt^2}$		+0.00011	
[19h 58m] cos E		−0.763	
[19h 58m] sin $E\frac{dE}{dt}$		−0.00615	radians per hour
	the equivalent of	−0″.353	per second

Second method.—Both formulas (1) and (2) are employed. The hourly change in A and D, and the velocity in α and δ per minute, are tabulated in the *Almanac*. It is convenient to reduce all these quantities (mentally) to seconds of arc per minute or per second of time, varying the factor in V_4 accordingly. All computations are accomplished with Crelle's *Rechentafeln* and three-place tables. The formulæ for V_3 and V_4, when $\frac{dE}{dt}$ is expressed in seconds of arc per second, are;

$$V_3 = -V_2 \cos E \ ,$$

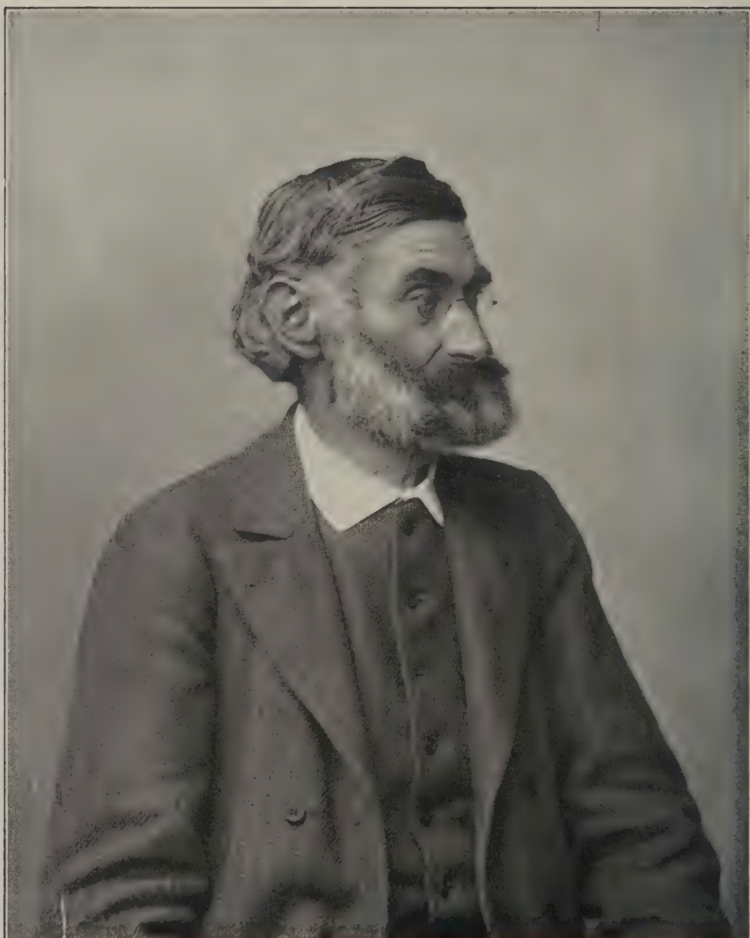
$$V_4 = [4.6856]\, D_2 \sin E \frac{dE}{dt} = 485 \times 10^{-8} \times D_2 \sin E \frac{dE}{dt} \ .$$

Example: Determine $\cos E$ and $\sin E \frac{dE}{dt}$ in seconds of arc per second of time.

1903, November 7^d 19^h 58^m

A	222° 16′	$\frac{dA}{dt}$ per second	+0″.042
D	−16 16	$\frac{d\alpha}{dt}$ per second	+0.619
α	84 30	$\cos(A-\alpha)\frac{d\delta}{dt}$	−0.009
δ	18 17	$\frac{dD}{dt}$ per second	−0.012
$A-\alpha$	137 46	$\frac{d\delta}{dt}$ per second	+0.012
$\sin\delta$	+0.314	$\cos(A-\alpha)\frac{dD}{dt}$	+0.009
$\sin D$	−0.280	$\cos(A-\alpha)\frac{d\delta}{dt}-\frac{dD}{dt}$	+0.003
Product	−0.088	$\sin\delta\cos D$	+0.3
$\cos\delta$	+0.960	I product	+0.001
$\cos D$	+0.950	$\cos(A-\alpha)\frac{dD}{dt}-\frac{d\delta}{dt}$	−0.003
$\cos(A-\alpha)$	−0.740	$\cos\delta\sin D$	−0.3
Product	−0.675	II product	+0.001
$\cos E$	−0.763	$(dA-d\alpha)/dt$	−0.577
		$\sin(A-\alpha)$	+0.672
		$\cos\delta\cos D$	+0.912
		III product	−0.354
		$[\mathrm{I}+\mathrm{II}+\mathrm{III}]\sin E\frac{dE}{dt}$	−0.352 per second of time

LICK OBSERVATORY,
UNIVERSITY OF CALIFORNIA,
March 11, 1905.



ERNST ABBE

Minor Contributions and Notes.

ERNST ABBE[1]

This distinguished authority on practical optics, to whom astronomical science is in no small measure indebted, died at Jena on January 14, after a long illness.

Born on January 23, 1840, at Eisenach, the son of an employee in a textile factory, his talents early attracted the attention of his teachers; and as a result, to a large extent through his own efforts, he was able to make his way through the university courses at Jena (1857–59) and at Göttingen (1859–61). At the latter university, after studying under Weber and Riemann, he took his degree with a thesis on the mechanical theory of heat. In 1863 he began teaching at the University of Jena as *Privat-docent*, and in 1870 was appointed *ausserordentlicher Professor*. For several years he had given assistance to Carl Zeiss, the mechanician at the Jena University, in his efforts in improving the microscope; and in 1875, at the earnest solicitation of Zeiss, Abbe became a silent partner in the firm of Zeiss & Co., the reputation of which rapidly developed. Abbe fulfilled the duties of his chair of theoretical physics and astronomy, besides those of the director of the observatory, until 1889, when at his own request, he was relieved, and thereafter gave only occasional lectures. In 1879 he entered into negotiations with Dr. Otto Schott, a practical glass-maker, with a view to the production of new kinds of glass for the requirements of practical optics. In 1882 Schott moved to Jena to devote his time to pushing more rapidly the experiments, which were first begun at Abbe's private expense. In 1884 the *Glasstechnische Laboratorium* of Schott und Genossen was established by Abbe, Schott, and Zeiss, father and son. Thereafter the financial assistance which had been given for two years by the Prussian government was no longer necessary. After the death of the senior Zeiss in 1888, and the withdrawal in the following year of his son from partnership, Abbe became the sole proprietor of the Zeiss works, but plans which he had had under way for some time finally resulted in

[1] The editors are indebted to Dr. Siegfried Czapski, managing director of the *Carl Zeiss Stiftung*, for the facts upon which this notice is based, and for the electrotype of the portrait of Dr. Abbe.

the establishment of the *Carl Zeiss Stiftung* as the sole owner of the optical works and as a partner of the glass works of Schott & Co. In 1891 Abbe transferred to the *Stiftung* all of his private property, so far as was permitted by law, and retained for himself only the position of a *Mitglied der Geschäftsleitung*, or director. Interest in his fellow-men was a passion with this university professor and successful business man, as is sufficiently evidenced by his contribution of this opportunity for large personal gain for the benefit of all his fellow-workers. An exceedingly interesting pamphlet of 145 pages, written by Professor Auerbach, of Jena, has recently been translated into English, and gives an excellent description of the great optical works, together with an explanation of the details of the numerous co-operative features of the *Stiftung*. Sociologists can find few more successful attempts at co-operation in a great common interest.

The most conspicuous scientific achievements of Abbe were: First, the development of the theory of the microscopic image of non-luminous objects. He published the elements of this theory in 1873, when it was quite contradictory to the prevailing teachings in optics; and he was constantly, though with frequent interruptions, occupied with its development. It was one of his warmest wishes, as well as that of his friends, that after he retired from the active direction of the optical works, he would find the time, so long denied, for a detailed statement of the results of his theory.

We should name as the second achievement in importance the establishment of the technics of the microscope in a rigorously scientific way upon computations involving all the elements, as radii, thicknesses, diameters, distances of lenses, and properties of the glass itself. On account of its difficulty, it was at the time hardly thought possible that this could be accomplished. The same thing had been effected by Fraunhofer for the telescope, and by Seidel and Steinheil for the photographic objective.

In the third place should be mentioned a number of remarkable optical and mechanical constructions, and numerous advances in recognizing the true nature of optical instruments. Under the one of these heads should be mentioned the Abbe refractometer, the apparatus for illuminating the microscope (1872), a system of homogeneous immersion (1878–79), the apochromatic lenses (1886), and the prism telescopes; under the other head should be enumerated the foundation of geometrical optics without reference to the means for their realization, the theory of the path of the rays, the theory of the light-power of optical instruments, and numerous contributions to the theory of errors of definition (*Abbildungsfehler*).

The full extent of the debt owed by astronomy and astrophysics to this university professor, efficient man of affairs, and conspicuous lover of his fellow-men, cannot yet be fairly realized. The microscopes, lenses, object-glasses, and prisms of the still "new Jena glass" are playing a part in the work of every active observatory; and Abbe's broad plan of establishing an impersonal institution which should call to its services the ablest talent in practical and theoretical optics will perpetuate its usefulness to science.

Reviews

An Introduction to the Theory of Optics. By ARTHUR SCHUSTER. London: Edward Arnold; New York: Longmans, Green & Co., 1904. Pp. xv + 340. $4.

Professor Schuster's book belongs to the broader and more modern treatises on optics of which Drude's *Lehrbuch der Optik* was the forerunner. The two books in matter and scope, speaking broadly, resemble each other, but the present one has the advantage of the four years' progress which has intervened between the two dates of publication, and by most students will be found a simpler, while in no way a less illuminating, means of approach to the broad principles which underlie this important branch of physics.

The work is divided into two parts. Part I is plainly intended as a systematic text for students entering upon the second stage of progress toward an understanding of the less involved principles of optics. Part II, which deals with some of the more general problems of radiation, has a far broader intention and is given, as necessity requires, a wholly different treatment.

Part I opens with a discussion of the kinematics and kinetics of periodic and wave-motions, followed by an introductory discussion of the nature of light and its propagation, together with a treatment of interference and diffraction, and a chapter on diffraction gratings. The theory of optical instruments precedes a discussion of the propagation of light in crystalline media and the interference of polarized light.

Part II, which will naturally prove the more interesting section to advanced students, begins with a chapter devoted to an exposition of the better-known theories of light, which is followed by a discussion of the problems of dispersion and absorption. Later chapters are upon "Rotary Effects," "The Transmission of Energy," and "The Nature of Light."

The work contains short biographical sketches of past leaders in theoretical optics, with some account of the work of each, and, what is even more important, shows the bearing of such individual contributions upon the progress of physics, thus affording an historical perspective which the student would not so easily reach for himself.

In the present volume the reader misses so full a discussion of the

problems of bodies in motion as that given by Drude; but as this whole matter in theory and experiment has not yet wholly passed out from the disputative stage, it is a compliment to the author's discretion that, for the purposes of such a book, he has held his peace upon it.

The most adequate idea which can be given of the range and purposes of the book, and the point of view of its author, is contained in the preface, from which two excerpts follow:

> There is at present no theory of optics in the sense that the elastic solid theory was accepted fifty years ago. We have abandoned that theory, and learned that the undulations of light are electromagnetic waves differing only in linear dimensions from the disturbances which are generated by oscillating electric currents or moving magnets. But so long as the character of the displacements which constitute the waves remains undefined we cannot pretend to have established a theory of light. . . . The equations which at present represent the electromagnetic theory of light have rendered excellent service, and we must look upon them as a framework into which a more complete theory must necessarily fit; but they cannot be accepted as constituting in themselves a final theory of light.
>
> The study of physics must be based on a knowledge of mechanics, and the problem of light will only be solved when we have discovered the mechanical properties of the aether. While we are in ignorance on fundamental matters concerning the origin of electric and magnetic strains and stresses, it is necessary to introduce the theoretical study of light by a careful treatment of wave propagation through media the elastic properties of which are known. A study of the theory of sound and of the old elastic solid theory of light must precede, therefore, the introduction of the electromagnetic equation.

The reviewer feels that Professor Schuster, by clearness of exposition and the painstaking work spent in the preparation of such a timely and useful book, has put students and teachers of physics under no inconsiderable obligation.

E. F. N.

Astronomical Discovery. By HERBERT HALL TURNER. London: Edward Arnold; New York: Longmans, Green & Co., 1904.

This new and very welcome book of Professor Turner's is neither a treatise nor a history, but, as explained in the preface, it is a series of half a dozen lectures upon certain important astronomical discoveries arranged "into a rough sequence according to the amount of 'chance' associated with the discovery." They are substantially the same as the course delivered at the University of Chicago in 1904, though with some changes and additions.

The subject of Chapter I is the discovery of *Uranus* and *Eros*. Chapter II deals at length with the discovery of *Neptune*, and presents some new material derived mainly from Sampson's recent memoir on the Adams MSS. Chapter III gives very fully the history of Bradley's discoveries of aberration and nutation. Chapter IV discusses some of the discoveries due to astronomical photography, and especially the remarkable phenomena presented by the "new star" of 1901. Chapter V is occupied with Schwabe's discovery of sun-spot periodicity; while, finally, Chapter VI treats of the variation of latitude, and especially of Chandler's work.

Like all of Professor Turner's writings, the book is readable and interesting; and also accurate and trustworthy, as much "readable" popular science is not. Matter which might easily become dull is enlivened by touches of humor and human interest, and by sententious bits of dry and witty wisdom. The author is especially intent to impress upon the reader how diligent labor and mere "luck" co-operate in the successful mining for scientific truth: how in the long run patient persistence in grubbing, as for instance in asteroid-hunting, often secures a rich return; while also, not infrequently, pure accident, and sudden opportunity promptly accepted, bring glorious successes.

Judged according to its scope and purpose, there is little fault to be found with the book, though many of its readers will probably confess to an Oliver Twist-like hankering for "more," and hope to have it gratified sometime in the not very distant future.

Possibly some may feel that Airy and Challis are rather hardly dealt with, especially the latter. It is, of course, quite true that if Challis had dropped everything else, and had daily reduced and compared his star-mapping work, he would have been the first to announce the new planet. But he had other pressing duties, among them a comet to be followed and observed; and comets wait for no man. Adams himself was clearly to blame for what looks like a sulky neglect to answer Airy's courteous inquiry; in fatal contrast to Leverrier's prompt reply to the same question, which led Airy to request Challis to undertake the search. Still it is not impossible that Airy's previous failure to urge the search, and his neglect to mention Adams in writing to Leverrier may have been partly due to pique at Adams' silence.

It seems, too, that the author hardly indicates how thoroughly both Adams and Leverrier were justified in assuming Bode's law as fixing the approximate distance of the hypothetical planet. First announced in 1774, the law had received brilliant confirmation in the discovery of *Uranus*, and again, twenty years later, in that of the asteroids. Any other assump-

tion would have been gratuitously unreasonable in 1845, and to work without some assumption, practically impossible.

Space does not permit more than to add that the other chapters are at least equally satisfactory, and that abundant credit is given to American astronomers, to one of whom the book is dedicated; indeed, it is possible that some of our German friends may feel that in the last chapter hardly enough credit is given to Küstner and the other observers who first authoritatively announced the variation of latitude as a fact, and organized the co-operative campaign which completely established it.

The volume is admirably printed (the only misprint we have noted is Winneche for Winnecke on p. 32), and has the crowning excellence of a good index.

C. A. Y.

Spectroscopic Observations of the Rotation of the Sun. By J. HALM. Reprinted from *Transactions of the Royal Society of Edinburgh*, Vol. XLI, Part I. Edinburgh, 1904. Pp. 16.

The comparative neglect of spectroscopic investigations of the Sun's rotation since the period of Dunér's famous publication must strike the attention of students of solar physics. This is the more remarkable because the periodic character of solar disturbances, and the interesting and complicated nature of the sun-spot cycle, cannot have failed to arouse the suspicion that a variation in the period of rotation of the reversing layer might accompany the changes in the state of the Sun's activity. Under these circumstances the most probable explanation of the failure of observers to undertake the investigation seems to lie in the practical difficulty of attaching apparatus of sufficient optical power to any of the ordinary refractors.

Dr. Halm's researches, accordingly, are of great interest, not only for the results obtained, but also because of the decided advance in the general character of the apparatus used. There can be no question, quite apart from considerations of the size of the instrument which can be employed, that in investigations of such a delicate character the spectroscope should be fixed in position. In the present instance this result was attained by the use of a siderostat, which projected a beam upon a heliometer placed in a horizontal position, which, in turn, formed the solar image upon the slit of the spectroscope, itself also horizontal and stationary. As the author himself remarks, it is easy to understand how a decided increase in the accuracy of measurement was obtained under such conditions of

stability and convenience, the probable error of a single observation amounting to but one-half of that found by Dunér.

Attention should, however, be called to one defect in the apparatus which will at once be recognized by anyone who has worked in stellar spectroscopy. This is the character of the illumination of the collimating lens of the spectroscope. Not only was the lens used of too great aperture to be filled completely with light from the image-forming objective, but the nature of the latter would have prevented full illumination even had this not been the case. The beams of light from the two sections of the heliometer objective, after passing through the slit, would fall on opposite sides of the collimating lens, which would be fully illuminated by neither. This would be liable to give rise to serious error, unless the lens were focused with very great accuracy, and at the same time, the entire instrument, including both lenses and the grating, were optically perfect. Such conditions it is almost hopeless to attain, and consequently grave doubt must necessarily be thrown upon some of the numerical results obtained by Dr. Halm. In spite of its great convenience and ease of manipulation, it is difficult to see how the heliometer can be employed in a spectroscopic investigation so exacting in its requirements as that of the solar rotation.

W. S. A.

PIETRO TACCHINI

We greatly regret to record the death on March 24, of Signor Pietro Tacchini, recently director of the *Osservatorio del Collegio Romano*, at the age of sixty-seven. Professor Tacchini has been an associate editor or collaborator of this *Journal* since its foundation, and the present development of solar physics owes much to his labors. We hope to publish in this *Journal* in due time an appropriate account of his life and works.

NOTICE

The scope of the ASTROPHYSICAL JOURNAL includes all investigations of radiant energy, whether conducted in the observatory or in the laboratory. The subjects to which special attention will be given are photographic and visual observations of the heavenly bodies (other than those pertaining to "astronomy of position"); spectroscopic, photometric, bolometric, and radiometric work of all kinds; descriptions of instruments and apparatus used in such investigations; and theoretical papers bearing on any of these subjects.

In the department of *Minor Contributions and Notes* subjects may be discussed which belong to other closely related fields of investigation.

Articles written in any language will be accepted for publication, but unless a wish to the contrary is expressed by the author, they will be translated into English. Tables of wave-lengths will be printed with the short wave-lengths at the top, and maps of spectra with the red end on the right, unless the author requests that the reverse procedure be followed.

Authors are particularly requested to employ uniformly the metric units of length and mass; the English equivalents may be added if desired.

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THE

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MONOCHROMATIC PHOTOGRAPHS OF THE *ORION* NEBULA

By J. HARTMANN

The thorough investigation of the physical condition and of the motions of the nebulæ is of fundamental importance as well for the understanding of the structure of the universe as for the history of its development. It therefore constitutes one of the principal problems of astrophysical research. But the observation of these objects is generally rendered so difficult by their faintness that it is necessary to employ special methods of observation and apparatus of great light-power; and this is particularly the case when the considerable losses of light due to the spectral dispersion are added. In what follows I desire to call attention to a phenomenon of importance in judging of the constitution of the nebulæ; and it will appear that this has been accomplished with comparatively simple instrumental apparatus.

It is well known that the losses of light in slit spectrographs are so great that, on attaching such an instrument to a large refractor, only a small percentage of the light falling upon the objective of the telescope reaches the photographic plate. The employment of an objective-prism has a decided advantage in this respect; and

therefore I constructed a few years ago an experimental, and hence small, spectrograph of this sort, which was arr nged as follows, with a view to attaining the greatest light-power. The optical parts were made of quartz for diminishing the absorption as far as possible, and their number was kept down to a minimum. The instrument accordingly had only a Cornu 60° prism and as a camera objective a simple quartz lens of the ratio $\frac{a}{f}=\frac{40\text{ mm}}{320\text{ mm}}=\frac{1}{8}$. The spherical aberration was overcome by Dr. Steinheil by local retouching.

This small and convenient quartz spectrograph proved, in fact, to have an exceedingly large light-power, particularly for the ultra-violet parts of the spectrum. For instance, a photograph of the nebula *G. C.* 4373, taken with an exposure of 150 minutes, showed fifteen lines of the nebular spectrum, while plates taken with the same exposure with the slit spectrograph attached to the great 80-centimeter refractor never recorded more than four lines. Plates of the *Orion* nebula taken with this apparatus, however, yielded a particularly interesting result; for they indicated that the different parts of the nebula emit light of different composition, and that extensive areas of characteristic form shine almost solely with ultra-violet light of the wave-length 3727.

The different monochromatic images into which the light of the nebula is separated by the objective-prism are, of course, very small, on account of the short focus of the camera lens: 1 mm on the plate corresponds to an angle of nearly 10′. This size was, nevertheless, sufficient to permit the form of the nebula to be distinctly recognized. While the images corresponding to the other lines of the spectrum were about alike, the image produced by the rays of the wave-length 3727 differed strikingly from them, extending out beyond the range of the other images by more than 10′, with intense and well-marked portions. At first glance it seemed as if the nebula had an entirely different form in the light of λ 3727 than in the light of the other colors; and it is only on minute examination that on long exposures an indication of the regions mentioned can also be detected in the light of the other lines, particularly of the two principal nebular lines, N_1 and N_2, at λ 5007 and λ 4959. In any case, the intensity of the rays of λ 3727 predominates so greatly that one may speak of an almost monochromatic ultra-violet light of the area in question.

So conspicuous a phenomenon could not have been wholly undetected in the very numerous earlier observations of the spectrum of the *Orion* nebula. Huggins,[1] who in 1882 first proved the existence of λ 3727 in the spectrum of the *Orion* nebula, as well as Campbell, who has made the most extensive studies on this spectrum, employed slit spectrographs. Hence they were able to reach conclusions only as to the spectrum of the small strip, the image of which fell upon the slit during the exposure. This strip had a length of 2'.5 on the plates of Huggins, and therefore contained a cross-section through the brightest part of the nebula, the so-called Huyghenian Region. Campbell's plates, for which the slit included an angle of about 7′, did not reach to the ultra-violet branches I have observed, which are more than 10′ distant from the trapezium. For the same reason the other observers who have used slit spectrographs have noted nothing of the phenomena.

The conditions were more favorable for observations made with the slit spectrograph, of which I will mention here the two following. In 1888 and 1890 W. H. Pickering made two photographs of the *Orion* nebula with the use of the objective-prism, which he describes in the *Annals of the Harvard College Observatory*, **32**, Part I, p. 75. He remarks that the line at λ 3727 was especially intense "along the southeast border of the Huyghenian Region, also in that part just west of the trapezium." According to this statement, the places remarked by Pickering lie close to the Huyghenian region, so that it would be hardly possible to identify them with the ultra-violet area observed by me. But the statement of Mitchell[2] as to the spectrum of the *Orion* nebula photographed by him directly with the concave grating of 60 cm focus accords well with my observation. He says: "The violet line λ 3727 has the greatest extent. The faint outlying regions show in this line a greater intensity and a greater extent than in $H\beta$. The Huyghenian regions appear about equally intense in λ 3727 and $H\beta$ . . . . " There can accordingly be no doubt that Mitchell also saw certain parts of the nebula solely in the light of λ 3727, although he gave no more precise statements as to their position. After I had established beyond a doubt the presence of these ultra-violet portions of the nebula, by several photographs

[1] *Proc. R. S.*, **33**, 425, 1881. [2] *Astrophysical Journal*, **10**, 34, 1899.

taken with the quartz spectrograph, I sought for some other way of determining more accurately their form and position and of following up the phenomenon further. I found a very suitable procedure for these investigations in the use of color filters with direct photographs of the nebula.

The employment of ray filters for astronomical purposes has been repeatedly suggested for the particular object of obtaining sharp pictures with a refractor achromatized for the visual rays. Lohse[1] reported on such plates in 1886. Similarly Spitaler[2] in 1890, and in 1900 Ritchey[3] made beautiful pictures with the great Yerkes refractor according to this method. The only attempt to use a color screen for investigating the relative intensities of the different spectrum lines in the *Orion* nebula was made by Keeler in 1899 with the Crossley reflector of the Lick Observatory.[4] He made, on the one hand, a photograph on an orthochromatic plate through a filter which transmitted only the first two nebular lines and $H\beta$, and, on the other hand, a photograph on an ordinary plate without a filter. From the comparison of the two plates he drew the conclusion that the light of $H\gamma$ and the other hydrogen lines (consequently also of $H\beta$) must be more intense than that of the two nebular lines N_1 and N_2 at those portions of the nebula which were impressed with a greater relative intensity on the second plate. This conclusion is, however, not valid, as is indicated by my plates presently to be mentioned, since the great photographic brightness mentioned by Keeler is not due to the light of $H\gamma$, but to the line λ 3727. But, as I desire expressly to point out, this error is without significance in respect to the fundamental idea of Keeler's investigation, namely, the proof that the light does not have the same spectral composition at all portions of the nebula.

For photographing through filters, the spectrum of the nebula may be divided into three sections, the first of which embraces the three lines of N_1, N_2, and $H\beta$—consequently the total light effective in visual observations. The second section extends from $H\beta$ about to the wave-length 3900 or 3800, and contains the series of hydrogen

[1] *Astronomische Nachrichten*, **115**, 1, 1886.

[2] *Annalen der k. k. Sternwarte in Wien*, **7**, 202.

[3] *Astrophysical Journal*, **12**, 352, 1900. [4] *Ibid.*, **9**, 133, 1899.

lines. In the third section, beyond λ 3800, lies the ultra-violet λ 3727 as the only conspicuous line. We may disregard the few other lines additional to those mentioned here also occurring in the spectrum of the *Orion* nebula, on account of their extremely slight intensity; and we may similarly neglect the faint continuous spectrum of the nebula.

I have attempted to produce filters which should be as transparent as possible for each one of the three sections, while they should wholly absorb the other two; and after extensive experiments I have adhered to the following, which accomplish the desired purpose very well and can readily be obtained anywhere.

1. *Filter of picric acid.*—An unexposed photographic plate is first fixed, and then bathed for several minutes in a concentrated solution of picric acid. The gelatine film assumes a very intense yellow color, and completely absorbs all the wave-lengths shorter than λ 4800, while it transmits the longer wave-lengths, hence especially the lines N_1, N_2, and $H\beta$, almost without loss.

2. *Filter of quinine-cobalt.*—A gelatine plate is similarly bathed in sulphate of quinine and used in connection with a blue cobalt glass. This combination transmits quite well the spectral radiation between λ 3880 and λ 3740, and absorbs all other rays.

3. *Nitroso-filter.*—If a gelatine plate is bathed in a concentrated solution of nitroso-dimethyl-anilin, it takes on a yellow color almost exactly like that of the picric acid screen, but it differs very decidedly from it in its absorptive action. Red, yellow, and green portions of the spectrum are transmitted almost without loss. Absorption begins at λ 5050, and then increases rapidly so that the absorption is complete even at $H\beta$; the lines N_1 and N_2, although very greatly weakened, are still transmitted. The heavy absorption extends to λ 4000; from there on the transparency increases rapidly, and λ 3727 is again well transmitted. The low transparency of this filter for N_1 and N_2 can be made harmless by using for those photographs a kind of plate which is not sensitive at this point; while contrariwise for the photographs used with the picric acid filter, plates are chosen which are as sensitive as possible in the blue-green.

By the simultaneous use of the first and third filters, photographs can also be obtained on which only N_1 and N_2 are effective, $H\beta$ being shut out.

I have employed these filters in securing a series of photographs of the *Orion* nebula with a Steinheil mirror of 24 cm aperture and 90 cm focus. The unfavorable weather which has prevailed during the latter months of the winter prevented me from carrying out the research to the full extent that I had planned; using every opportunity for observation that was in any way available, I was able to get only the following plates in two months.

Plate	Date	Filter	Exposure
3	1905, Jan. 23	Nitroso	45 minutes
5	" 25	Nitroso	120 "
7	Feb. 13	Quinine-cobalt	30 "
8	" 13	Picric acid	7 "
9	" 26	Picric acid	120 "
10	" 27	Quinine-cobalt	56 "
11	" 28	Quinine-cobalt	10 "
12	Mar. 1	Quinine-cobalt	60 "

The sky was entirely clear only on January 25; on all other evenings mists arose and disturbed the observations, as is shown by the very short exposures in some instances. These few plates have, nevertheless, already led to several interesting results, which I would point out in connection with the accompanying reproductions. Plate XX is a sixfold enlargement of photograph No. 5 taken with the nitroso-filter. Plate XXI is an enlargement of photograph No. 9 taken with the picric acid filter. The sketch in Fig. 1 makes no attempt to accurately represent the appearance of the nebula, but is only for facilitating the identification of the regions referred to. The scale of the three figures is $1 \text{ mm} = 40''$.

We should note, in the first place, the extraordinary intensity of the line λ 3727 in *all* parts of the nebula. Photograph 5 (Plate XX), taken with two hours' exposure with the nitroso-screen, gives an image of the nebula 45′ in diameter, in which a great number of details of structure can be recognized. This ultra-violet light is also the principal emission of even the most outlying and faintest portions of the nebula, which are mostly lost in the reproduction. I also got the impression that the condensations of the nebulous mass which give the *Orion* nebula its peculiar appearance of motion are most sharply represented in the ultra-violet light, while the light from the hydrogen lines seems rather to form a uniform background.

PLATE XX

THE *ORION* NEBULA
Monochromatic Photograph with Light of Wave-Length 3727

PLATE XXI

THE *ORION* NEBULA
Photographed with Light of the Lines N_1, N_2, and $H\beta$

Along with this general diffusion and intensity of the ultra-vio'et light, by which it is possible to obtain a complete photograph of all parts of the nebula through the nitroso-screen, this light also comes out with particular intensity at certain places. In this respect, the most interesting illustration is shown in the case of the series of strips

FIG. 1.

shaped like arcs, 14′ west of the trapezium, designated in the drawing by *AB*, which constitutes the ultra-violet portion, earlier discovered with the quartz spectrograph. In this section the light of the lines N_1 and N_2, as well as of the hydrogen lines, is so faint that this area

is entirely invisible to the eye, although it constitutes one of the most striking objects on every plate taken with the reflector. As stated above, Keeler erroneously ascribed the light of this region to the hydrogen lines, hence particularly to $H\gamma$.[1]

The second region obtained by Keeler on his plate with the Crossley reflector, the strip marked CD, parallel to the *Proboscis Major*, DE, similarly does not shine with hydrogen lines, but in that of λ 3727. It is so intense that this region on the plate taken with the nitroso-filter looks entirely different from that on the drawings of the nebula representing visual observations, and also from that on plates taken with objectives, which, of course, always absorb the ultra-violet light strongly. On refractor plates the *Proboscis Major*, DE, is always striking, having its sharpest boundary on the western side; and it constitutes a characteristic form particularly at the slight curve surrounding the star Bond 784 at D, while Keeler's strip CD is hardly visible. But in the ultra-violet light this strip is quite as bright as the most intense portions of the *Proboscis Major*, and at D mingles with the latter to such an extent that the star mentioned is entirely overpowered.

The two regions mentioned, AB and CD, are very faint in the light of the nebular lines N_1 and N_2, as appears from Plate XXI; but they are nevertheless still fainter in the light of the hydrogen lines. The small condensation at H is particularly bright in the ultra-violet light; it is hardly suggested on the photographs through the quinine-cobalt filter, while the stars Bond 373 and 382 north of it, which are wholly overpowered by the nebula on Plate XX, come out very distinctly.

I have indicated on my sketch by heavier horizontal shading the other portions of the nebula which are conspicuous for their ultra-violet radiation. As may be seen, they are principally exterior portions of the Huyghenian region, particularly the arc-shaped northern boundary which extends toward F from the trapezium, as well as a streak extending from the trapezium toward A. The ultra-violet light seems also to predominate in the portion of the nebula indicated by dots. I have not yet, however, been able to determine to what degree this is the case, as I have not yet had a

[1] *Astrophysical Journal*, **9**, 142, 1899.

chance to make sufficiently long exposures in the light of the *H* lines with the quinine-cobalt filter.

I will here briefly call attention to two other phenomena. First, the light of the lines N_1 and N_2 is almost wholly lacking in the nebula *G. C.* 1180 (*V* 30) which surrounds the star *c Orionis*, 35′ north of the trapezium. Hardly a trace of the nebula appears on the plates made through the picric acid screen even with two hours' exposure (see Plate XXI), while it is beautifully depicted on the other plates, especially with that taken in ultra-violet light (Plate XX). The light of the hydrogen lines is also rather bright in this nebula, whence its easy visibility to the eye in spite of the faintness of N_1 and N_2.

The second remark refers to the intensity of the star disks, which display marked differences in certain cases for the different filters. Thus hardly any traces of many of the stars appear even on the two-hour exposure (No. 5), which are impressed on photograph No. 8 in the green part of the spectrum with an exposure of only seven minutes. I will cite here as examples only the stars Bond 402 and 430. I shall later undertake the complete enumeration of such objects when there is available for the middle section of the spectrum as good a photograph as I have for the exterior portion of the spectrum. When these stars lie in the nebula itself, it is difficult to decide with certainty whether the apparent difference in brightness is not principally due to the photographic concealment of the star image by the nebula. This question could be easily decided by a repetition of the filter plates with an instrument of longer focal length. For the stars lying without the nebula, we probably can explain the different intensity on the different filter plates only as an effect of the type of the spectrum. The assumption made hitherto—that the faintest stars in the neighborhood of the *Orion* nebula also belong to the first type, as is the case for the brighter ones, the spectra of which have been investigated—is now fully confirmed in a general way by the photographs through the color screens, since the ratios of intensity agree for nearly all the stars in the visual (Plate XXI) and in the ultra-violet portions (Plate XX) of the spectrum. The few stars which are depicted in greater relative intensity through the picric acid filter may be assumed to belong to the second or even the third spectral type.

The observations here communicated thus confirm anew, first, the fact, suspected by Huggins and later proved beyond a doubt, particularly by Campbell, that the light of the *Orion* nebula is not homogeneous, but of different composition in the different regions. The conclusions which have hitherto depended upon the different behavior of the nebular lines N_1 and N_2, as compared with hydrogen lines, are now extended also to the line λ 3727. According to all previous estimations, the ratio of intensity of the lines N_1 and N_2 is constant in all nebulæ, and also in the different parts of the *Orion* nebula, as was established with the greatest certainty by the measurements of Wilsing and Scheiner.[1] If the conclusion should be drawn from this that these two lines belong to the spectrum of the same gas; and if it is rendered probable from the varying ratio of intensity from that of the hydrogen lines that this gas is different from hydrogen; then it is now proven, by the still different behavior of the intensity of the line λ 3727 from that of the two groups of lines just mentioned, with an equal degree of probability, that there occurs in the nebulæ at least a third gas, additional to the other two, partly mingling with them, but also partly separated in space from them. It is not very likely that this third gas is oxygen, which has a rather strong line at λ 3727.5, while the best determination, by Wright,[2] yielded the value λ 3726.4 for the wave-length of the nebular line. Inasmuch as this determination is, however, not yet very accurate, it would be desirable to have the wave-length of the two lines determined as sharply as possible.

It has already been repeatedly pointed out, and it is confirmed anew by the observations here described, that it is an essential condition for the proof of any changes or motions in a nebula that only photographs of the object in question taken under precisely similar conditions should be compared. Ray filters are of the greatest value just for securing these constant conditions, since they render harmless all the sources of error due to the color sensitiveness of the brand of plates used for the photograph, as well as the selective absorption of the optical parts of the instrument and of the atmosphere. For example, if plates having almost the same curve of

[1] *Astronomische Nachrichten*, **159**, 181, 1902.

[2] *Astrophysical Journal*, **16**, 53, 1902.

sensitiveness are exposed through the nitroso-filter, and are developed to an equal density, then they are directly comparable; such a comparison, which may be made with the Zeiss stereocomparator, will lead, though perhaps not for some decades, to the determination of the motions taking place in the nebulæ, which are up to the present wholly unknown.

Astrophysikalisches Observatorium,
Potsdam, March 24, 1905.

HIGH-TEMPERATURE RADIATION

By P. G. NUTTING

Stellar spectra bear a striking resemblance to the spectra of gases conducting an electric current in the form of an arc, spark, or vacuum-tube discharge. Yet we can hardly conceive of an excitation of radiation that might be common to stellar and arc spectra. Nor can we imitate stellar spectra by mere thermal excitation; at least not by merely heating an elementary substance up to 1,500°. Hence it would appear that the radiation of a body at the higher stellar temperatures is quite a different process from the radiation from a body at a temperature of 1,000° to 2,000°. And although the manner of excitation may be quite different, the processes of radiation at very high temperatures appear to be essentially the same as those involved in the radiation from an arc or Plücker tube. It is the purpose of this investigation to examine in detail the processes involved in the electrical, mechanical, and thermal excitation of radiation, and, on the other hand, to trace back lined spectra and black-body spectra to a system of radiators consistent with the electromagnetic theory of radiation, and with the atomic and kinetic theories of the structure of matter. Many of the conclusions reached are, of course, only tentative at best, since direct experimental tests are beyond our facilities, and astrophysical evidence is too meager to be conclusive.

RADIATION PROCESSES INVOLVED

We are here concerned with the transformation of mechanical, electrical, and thermal energy into the energy of radiation, and are to determine under what conditions and within what limits these three forms of excitation may produce similar radiation of a given character. So far as spectroscopic evidence alone is concerned, it must be admitted that the problem is indeterminate. Sufficient conditions (for radiation) far outnumber the necessary conditions; many different forms of radiators might give the radiation observed. Nor can the electromagnetic theory of light and of the dynamics of moving charges of itself furnish a sufficient number of independent

sets of conditions to make the problem determinate. The atomic theory of matter and the theory of electrical conduction are inadequate as well. But all four sets of conditions taken together appear to supply sufficient independent data to make the problem determinate.

Electromagnetic theory indicates that electromagnetic radiation must originate in an electromagnetic disturbance of some kind; that is, in a variable electromagnetic field, either a stationary field varying in intensity or a steady field in motion with a variable velocity. This is a *necessary* condition. Larmor, Lorentz, Heaviside, and others have even calculated the rapidity of variation or the amount of acceleration necessary to produce a given amount of radiation of a given character. A constant field does not lose energy, nor can the motion of an uncharged, unmagnetized body through such a field cause radiation; much less could the motion of such a body *not* within such fields.

The atomic theory with the kinetic theory of gases supplies evidence for the existence of moving particles having the necessary dimensions, elastic constants, and degrees of freedom. The modern theory of electrical conduction indicates that these moving particles carry electrical charges of certain amounts in a given manner. The combined evidence is then that atoms and molecules are neutral aggregates of charged particles whose individual motion originates electromagnetic radiation. Now, spectroscopy shows that the emission of lined spectra, of black-body spectra, and of many intermediate forms, are to be accounted for. To do this consistently with the atomic theory, the electromagnetic theory, and the theory of electrical conduction, it is necessary and sufficient that there be present in a radiating body one or all of the three following types of radiators:

(1) Neutral aggregates of charged particles—atoms, molecules, or groups of molecules, in general all three—possessing a motion of translation and, in general, rotatory motion about some axis. Neither motion is directly concerned with radiation. When undisturbed from without, such neutral aggregates would so arrange themselves as to have no external field, and hence would not start electromagnetic waves, whatever their motion of translation or rotation. But disturb the equilibrium of the arrangement—by a violent impact with a

neighbor, by bombarding it with charged particles having a very high velocity, or by sending past it a sharp electromagnetic wave or pulse—and it will possess a temporary external field; this external field, alternating as the aggregate oscillates through its equilibrium formation and regains its original steady state, will start electromagnetic waves. Rings of negative electrons rotating about or within a positive kernel, forming such systems as have been discussed by J. J. Thomson and Nagaoka, would be possible types of this class of aggregates.

(2) Aggregates electrically neutral or not, as to total charge, but with parts relatively so widely separated, so few in number, or so arranged that there is considerable local field. Such an aggregate need but to rotate to produce an alternating field, and hence send off an electromagnetic wave. A system having a structure like the solar system, or like the hydrocarbon molecule imagined by chemists, would be typical of the class of aggregates.

(3) Free charged particles torn from the neutral aggregates of classes (1) and (2), and moving independently. These charged particles possess an electromagnetic field, and radiate when this field changes, i. e., when the velocity is changed. The amount of radiation is proportional both to the velocity and to the acceleration. Impact and orbital motion would be the chief causes of acceleration.

Radiation from aggregates of class (1) would be due to the rapid oscillatory motion, radial, transverse, or tangential, of the charged parts of the aggregate, and hence would be characterized by a definite period. Stronger excitation would produce more intense radiation without affecting the period. This period would be very small, on account of the great forces involved in such stable equilibrium, and would have an upper limit rather sharply marked. On the other hand, radiation from sources of the second class, depending on central acceleration, would vary in period with each impact. The various periods radiated would be distributed about a mean, which would depend upon the average rotatory energy before collision and upon the velocity of impact; i. e., it would vary with the temperature. Sources of the third class would be relatively of little importance in producing ordinary radiation from a gas—except when intense electric currents are concerned—on account of the

relatively small number present and the rapidity with which recombination takes place. In metals they are much more numerous, and appear to play an important rôle in radiation. The radiation caused would of course—like that from sources of class (2)—have no definite single period.

Having traced radiation back to three possible sources consistent with kinetic theory, spectroscopic phenomena, and the theory of electrical conduction, let us consider the various means, mechanical, electrical, and thermal, of exciting these sources to radiation. The process of breaking up a neutral aggregate into parts not neutral we shall refer to, for short, as *ionization*, the charged parts being called ions; in chemical ionization the parts are of the same order of magnitude, while electrical ionization is a tearing away of one or more of the smallest charged particles of which the neutral aggregate is composed. On the convection theory of electrical conduction, conductivity of course *implies* an ionized state of the conductor. A measurable conductivity requires that something like one molecule in 10^{12} be ionized, while a conducting gas gives sufficient luminous radiation to be perceptible when about one molecule in 10^7 is ionized, and experiment shows that the luminosity increases in proportion to the current, i. e., in proportion to the number of molecules ionized. Luminosity appears to be always accompanied by ionization, i. e., by electrical conductivity, even in cases of fluorescence. A study of electrically excited gases indicates that recombination is the chief cause of the violent agitation of the aggregates of class (1) above which radiate lined spectra.

ELECTRICAL EXCITATION

Application of a steep potential gradient to a gas pulls the oppositely charged parts of neutral aggregates in opposite directions, and if the gradient be great enough, it will ionize the gas and allow a current to pass. In the steady state the rapid recombination is balanced by fresh ionization, caused chiefly by the bombardment of neutral aggregates by the convection of charged particles—positive and negative ions—constituting the current. The energy necessary to ionize a molecule may be calculated from the fall of potential—about 5 volts for air, hydrogen, and helium—through which a charged

particle must run in order to gain[1] sufficient impetus to ionize a molecule by impact. $E=(V_2-V_1)e=5\times10^8\times1.1\times10^{-20}=5.5\times10^{-12}$ erg per molecule. This is 3.3×10^8 ergs, or 7.8 calories per cubic centimeter of gas at 0° and 760 mm, and appears from the work of Davis (*loc. cit.*) to be very nearly the same for the different elementary gases, but considerably—50 per cent.—greater for a compound gas like CO_2. Reduced to mass units, 7.8 calories per cubic centimeter is for air 6,000 calories per gram, and for other gases in inverse proportion to the atomic weight. This is an amount of energy approximately 100 times that required to vaporize air, and eleven times that required to vaporize water.

If, then, an ionization of one molecule in 10^7 be required to render a gas visibly luminous, this would require an expenditure of 10^{-5} ergs of electrical energy to excite to visible luminosity sources of lined spectra—class (1) above. In a metal the permanent conductivity indicates permanent ionization, while the character of the radiation indicates that it comes from sources of classes (2) and (3). Now a metal becomes visibly luminous when radiating energy at the rate of about 3 watts per square centimeter of surface. Hence, assuming a molecular diameter of the order of 10^{-7} centimeters, we would have 3×10^7 ergs radiated by 10^{14} molecules, or 3×10^{-7} ergs per molecule. If all the radiation were luminous, instead of less than 1 per cent., only about 10^{-9} ergs per molecule would be required to excite luminosity in a (solid) metal. This is less than a thousandth part of that required to ionize and render luminous a molecule of a gas or vapor.

The ionization in a metallic solid appears to be largely due to the proximity of the molecules, causing an overlapping of adjacent electromagnetic fields; a weakening of internal conservative forces, or an overbalancing of internal by external forces, however we choose to regard the process. Probably the nearest analogue is the solution of a salt in water. The radiation from a highly compressed gas would, of course, take on more and more the character of the radiation from a heated solid, as the molecules are forced nearer and nearer together; that is, radiators of the first type would become radiators of the second and third types. Hence the assumption of

[1] B. Davis, *Phys. Rev.*, **20**, 145, March 1905. Townsend, *Phil. Mag.*, (6) **1**, 209, Feb. 1901.

a damping mechanism is by no means necessary to account for the broadening of optical spectral lines and the emission of a continuous spectrum.

A metal of course loses its ionization on being vaporized, for a metallic vapor is no more a conductor than hydrogen or air until it is ionized. The energy required for ionization would make the heats of vaporization of metals low, and thus is an important factor in solar and stellar phenomena.

There is a third form of electrical excitation, namely, that caused by the passage of an electromagnetic wave or pulse, like optical or Röntgen radiation. Such a wave or pulse would of course tend to jerk apart positive and negative charges. But a simple calculation shows that to impart 10^{-5} erg to a molecule would require a wave of such short period, or a pulse so thin, as to be beyond the limits one could assign to ultra-violet and Röntgen radiation. But when a gas is just at the point of being ionized by other means, these forms of radiation are undoubtedly important factors in helping to complete the ionization.

MECHANICAL EXCITATION

Mere translation through space would be sufficient to ionize a body, and hence produce intense radiation, provided the velocity be great enough. From the dynamics of moving charges we know that if two electric charges are moving together, the electric forces acting between them are opposed by the magnetic forces arising from their motion. The expression for the resultant electromagnetic force between the two charges always contains the factor $1-u^2:V^2$, in which u is the velocity of the charges and V the velocity of light, whatever their orientation. Hence, when moving with the velocity of light, any aggregate of particles, neutral or otherwise, held together by electrical forces, would become unstable. A neutral aggregate broken up by this means would thus become a group of separately moving charged particles, hence would lose—and absorb—energy at a tremendous rate, would recombine as a radiator of type (1), and would therefore give off intense optical radiation of definite period. The energy required for such mechanical ionization—$\frac{1}{2}m\,u^2=\frac{1}{2}(2\times10^{-23})\;(3\times10^{10})^2=10^{-2}$ erg per molecule—is a thousand times as great as that required for ionization by other—e. g., elec-

trical—means, hence we should look for ionization of this class only in stellar explosions and the like. The radiation from *Nova Persei* may well have been due to mechanical excitation of this type.

Given the Maxwell-Boltzmann distribution of the velocities of the molecules of a gas, and assuming that this distribution-curve is displaced toward higher velocities at higher temperatures, one might expect a few molecules at high temperatures to attain ionizing velocity. But calculation shows that a temperature of millions of degrees would be required—a temperature far greater than that sufficient to ionize the gas by other means discussed in the following paragraph.

THERMAL EXCITATION

Heating a body, say a gas, would tend to ionize it, and hence cause it to radiate by each of two processes; heating would increase mean molecular velocity, and hence violence of impact, and it would increase internal molecular energy, and hence weaken internal conservative forces. Let us calculate the temperature at which the mean molecular energy is equal to the energy (page 5) required to ionize a molecule by electrical means. Specific heat is sufficiently independent of temperature[1] for our purpose, and may be taken as about $\frac{1}{4}$ calorie per gram. This is about 2×10^{-16} erg per molecule per centigrade degree. Hence, at a temperature of $(5\times10^{-12}\div 2\times10^{-16}=)2.5\times10^{4}$ degrees absolute, a body would possess sufficient internal energy to completely ionize it. It would possess sufficient energy to be ionized sufficiently to be intensely luminous at a much lower temperature—about 2,500°—if the distribution of molecular energy about the mean is anything like that given by the probability function.

Assuming then only the equivalence of thermal and electrical energy, and taking the value—5.5×10^{-12} erg per molecule—for the energy of ionization obtained by electrical methods, we may draw two very important conclusions. First, that at a temperature of about 3,000° every body, even a pure isolated gas, should become luminous. Secondly, there is a fixed upper limit—about 10,000°—to the temperature to which it is possible to heat a body. It could not be heated electrically to a higher temperature, because there would

[1] Holborn and Austin, *Sitzungsberichte der k. p. Akad. d. Wiss. zu Berlin*, Feb. 2, 1905.

be no more ions to carry a greater current, nor heated thermally, on account of the tremendously rapid loss by radiation as well as the limit to the rate at which thermal energy could be conducted to the body. We may speak of this roughly defined upper limit to temperature as the *ionization temperature*, just as we speak of the temperatures of vaporization and of fusion.

Let us examine the possible effects of chemical combination on ionization temperature and luminosity. If the combination is exothermic, and the process is *continuous*, as in a flame, the extra heat liberated would of course depress the ionization temperature, and thus the temperature at which luminosity occurs. But if the compound gas forms an isolated body and is merely heated, or if it is conducting an electric current, ionization and recombination occur alternately, and on the whole as much energy will be absorbed as liberated. However, another effect comes in which *would* depress the ionization temperature; namely, the weakening of internal forces by the proximity of aggregates discussed above. This effect would depend upon molecular and atomic mass and structure, rather than on the energy of combination, and, like excessive compression or condensation, would depress the ionization temperature in every case.

The relation of spectral radiation to black-body radiation cannot be discussed here, but, applying the laws of black-body radiation to solar and stellar radiation, as a first approximation, we find strong evidence of the existence of an ionization temperature; that is, there appears to be a fixed upper limit—of about 7,000° to 10,000°—to temperature which is not exceeded by any star. Further, the similarity of stellar spectra to the spectra of gases conducting an electric current is just what would be expected if the mechanism of radiation be that here discussed. Further, Nasini and Anderlini[1] have succeeded in obtaining the red end of the nitrogen spectrum by merely heating pure nitrogen to a temperature of about 3,000°. Liveing and Dewar,[2] King,[3] and others, by vaporizing various metals at a similar temperature, have obtained lined spectra, but the possibility

[1] *Rend. ac. dei Lincei,* (5) **13**, 59–66, 1904.

[2] *Proc. R. S.*, **34**, 119, 1882.

[3] *Annalen der Physik*, **16**, 360–382, Feb. 1905.

of chemical changes occurring at the same time was not excluded, hence the excitation of the spectral radiation observed might not have been directly due to purely thermal causes.

The word "temperature" has been used in this paper in its thermodynamic sense, as the argument of the energy-content function, rather than in its kinetically defined sense. The ordinary kinetic theory of course does not hold for any ionized body, that is for any body which is a source of radiation of an electromagnetic nature. If, then, the application of the notion of temperature to heated solids —containing radiating sources of types (2) and (3)—be logical and useful, why should it not then be as applicable to incandescent gases containing sources of the first type as well as of the second and third? I do not see that the greater rate of loss of energy by radiation, or the limitation of this radiation to a few periods, presents any essential difficulties to the rigorous definition of energy-content. Jeans[1] has extended the kinetic theory to cover a sort of generalized molecule having n degrees of freedom of one class and r of another class, and subject to dissipative forces, but the limits to the thermodynamic definition of temperature permit a still more general kinetic theory. We might have not one, but several kinds of moving particles possessing electromagnetic as well as mass inertia, subject to elastic and dissipative forces of any nature. The seat of this energy may be partly in the adjacent field, as well as within the particles. So long as the heterogeneity does not extend to the mean direction of motion of the particles, so long as a vector definition of energy and temperature is not required, we shall have no difficulty in constructing a thermodynamic definition of temperature. But in a gas conducting an electric current, there is such heterogeneity even in finite regions, that rather than to attempt an extension of the term "temperature" to cover this case and the case of gases so rarified that the free path is of finite length, it would appear advisable to limit the use of the term to bodies possessing only infinitesimal heterogeneity of distribution of energy; that is, to cases to which statistical methods are applicable.

SUMMARY OF CONCLUSIONS

Electromagnetic radiation may originate in material bodies when

[1] *Phil. Trans.*, **196**, 397–430; May 22, 1901.

these bodies contain sources of one or all of the three following types:

1. Electrically neutral aggregates of charged particles that possess no finite external electromagnetic field when undisturbed.

2. Aggregates possessing a finite external field, which may or may not be electrically neutral as to total charge.

3. Individual charges or charged particles moving independently of one another and of aggregates of particles.

Excitation of an electrical, mechanical, or thermal nature suffices to excite these three types of sources: type (1) to lined spectral radiation, types (2) and (3) to radiation of the black-body type.

To account for the broadening of spectral lines or the emission of continuous spectra, it is unnecessary to assume damping of the radiator.

Bodies possess in general, not only a fusion temperature and a temperature of vaporization, but an *ionization temperature* lying within the range of from 3,000° to 10,000° for elementary gases, and lower for other substances.

Purely thermal heating of a body to the neighborhood of its ionization temperature is sufficient to cause radiation.

It would be difficult, if not impossible, to heat a body by electrical or thermal means above its ionization temperature; hence there is an upper limit not exceeded by stellar temperatures.

Bureau of Standards,
Washington, D. C.,
April 1905.

SPECTRA OF WEAK LUMINESCENCES. II

THE THERMO-LUMINESCENCE SPECTRUM OF FLUOR-SPAR

By HARRY W. MORSE

That many substances become luminescent on being heated to a temperature far below that of incandescence has been known for a very long time, and descriptions of these phenomena may be found in nearly all of the reports on "phosphorescence" which were frequent forty or fifty years ago.[1] Among thermo-luminescent substances two have been especial objects of interest: luminescent diamonds, which were known at least as far back as the time of Boyle, and the mineral fluor-spar. Some thermo-luminescent crystals were sent to the French Academy of Sciences in 1724, and from the description of the results of the examination made of them it would seem certain that they were crystals of fluor-spar.

The general appearance of the light emitted by these substances when they are heated has been frequently studied and described. Becquerel gives a quite complete résumé of the observations of French and English scientists on these phenomena,[2] and he made also a number of experiments on the relation of temperature and luminescence, and on the regeneration of the luminescence by light and by the electric spark, after the power to emit light had apparently been exhausted by continued heating. He also drew some conclusions with regard to the relation between the color of the crystals and their thermo-luminescence. Becquerel's account of the work of the German scientists is by no means so complete, and many interesting points connected with the phenomena in question are to be found in the researches of Osann, Fiebig,[3] and others. In the research of Fiebig an important question is brought up, namely, whether a substance must at some previous time have been exposed to light in order that it shall exhibit thermo-luminescence. The

[1] Among the older researches those of Wedgewood, *Phil. Trans.*, 1792, and Brewster, *Edin. Phil. Mag.*, **1**, 383, contain especially large lists of thermo-luminescent substances.

[2] *La Lumière*, **1**, 22, and 43. [3] *Pogg. Ann.*, **114**, 292, 1861.

evidence offered is not conclusive, but later researches have shown that a substance may exhibit strong thermo-luminescence without having been exposed to any light for at least many thousand years.

Data on the spectrum of the light emitted by thermo-luminescent substances is almost entirely lacking. Becquerel himself, who usually had no fear of weak luminescences, and who examined with apparatus giving considerable dispersion many spectra of phosphorescence, admits that he was unable to analyze the light from thermo-luminescent substances with any satisfactory results. I have found only one reference which suggests that the author really observed a spectrum of the same kind as those which I have photographed, and that is a brief note in *Poggendorff's Annalen* "from a letter from Herr Kindt."[1] The statement is here made that the spectrum from a certain crystal of fluor-spar is not continuous, but has strong dark bands in it "much like the absorption bands in the spectrum of the didymium salts."

The general facts concerning the production of a thermo-luminescence may be briefly summarized as follows:

1. Certain minerals (fluor-spar, diamond, leucophane, apatite, scheelite, etc.) and many artificially prepared sulphides of the alkaline-earth metals, as well as many salts, emit light when heated to a temperature below that of incandescence.

2. These substances appear without exception to exhibit fluorescence or phosphorescence, or both, under excitation by light, but many of the most brilliantly thermo-luminescent substances are not at all brilliant in fluorescence or phosphorescence, and many brilliantly fluorescent or phosphorescent substances exhibit no measurable thermo-luminescence.

3. There appears to be, for each substance, a quite definite relation between the time of heating, the temperature, and the intensity of the luminescence. Some phosphorescent sulphides may be exhausted of thermo-luminescence at a high temperature in a few seconds, while the luminescence of a crystal of fluor-spar may be either exhausted in a minute or so (at a red heat), or may persist for many hours at nearly constant intensity (at, say, 100° C.). Measurements of the relation between temperature, time of heating, and intensity of emitted light have not yet been made.

[1] *Ibid.*, 131, 160.

4. The temperature at which light begins to be emitted by these substances may be a comparatively very low one. Some specimens of chlorophane and certain diamonds (especially Brazilian ones) are sensitive enough to show luminescence plainly when warmed by the hand, and many other substances show the effect brightly when heated to 200° C.

5. In many cases the entire store of light contained in the substance does not appear to become exhausted by heating to a temperature lower than a certain definite maximum, no matter how long the heating is continued. For, after all emission of light has ceased at a low temperature, more is produced by raising the temperature to a higher point, and when the light supply at this higher temperature has become exhausted, still more may be obtained by another increase in temperature. There appears, however, to be a certain maximum temperature at which all of the store of light in the substance is exhausted, and further increase of temperature beyond that point does not result in further luminescence.[1]

6. On standing in the dark the power to emit light on being heated is not regenerated. With respect to the regeneration of this power by light or by the action of the electric spark, various substances show differences so great as to make it certain that the phenomena are complex in their nature, and connected with more than one cause. The phosphorescent sulphides are easily regenerated by a short exposure to light, as would natural y be expected from the method of their preparation. But crystals of chlorophane (the name is appl:ed to a variety of fluorite which xhibits a strong green thermo-luminescence) cannot be restored to their original condition by any amount of exposure to either light or the electric spark. They may be given the power to thermo-luminesce with another (usually purple or lavender) color in much less intensity, but they never recover the power of emitting the original bright green.

The present paper contains data on the spectra of thermo-luminescence of two distinct varieties of fluorite, one a "chlorophane" from Amelia Court House, Va., and the other a common, clear, color-

[1] See Le Bon, *Revue Scientifique*, 14, 289 and 327. My own results agree with those of Le Bon so far as the facts connecting temperature and light-emission are concerned. With some of the conclusions drawn I should not agree.

less (or very slightly greenish) specimen from Westmoreland, N. H. Both are slightly fluorescent under the influence of ultra-violet light, the fluorescence color being the usual lavender common apparently to all fluorites under these conditions; and both are phosphorescent, exhibiting the lavender-colored light for some time after exposure to the spark. Neither is at all brilliantly fluorescent or phosphorescent under any circumstances in which I have so far placed them; but both are very strongly thermo-luminescent, the chlorophane emitting a very strong bright green light, perfectly visible in a well-lighted room, and the other fluorite emitting a lavender or purple light, not very different to the eye from the light emitted by the same substance in fluorescence and phosphorescence.

Results of more directly physical and chemical interest will be taken up more fully in another place. Of especial spectroscopic interest are the thermo-luminescence spectra of these two minerals and certain relations existing between them.

Examined visually (with a small direct-vision spectroscope) the light from either substance gives a discontinuous spectrum. The chlorophane yields a nearly continuous band with the maximum in the green-yellow, and, superimposed over this, a series of sharp lines. The light from the other fluorite consists of several broad bands of diffuse nature, with a sharp-line spectrum above them. The broad bands in the two spectra make up the greater part of the emitted light, and the lines are much obscured by their presence.

Close examination of the chlorophane shows that there are at least three distinct stages in the light-emission. At a low temperature (50°–100°) the green light appears. After this has begun to grow dim with increasing temperature, a yellowish color of less intensity and shorter duration takes its place, to be in turn replaced by a weak lavender luminescence at still higher temperature. This last color is much like that of the fluorescence under the influence of light. The luminescence during the two later stages of heating the chlorophane is so feeble and evanescent that photography of the spectrum of each stage separately seems to be a very difficult task. In the case of the colorless fluorite I have not been able to separate distinct stages differing markedly in color, but it is evident that the light produced at higher temperature, toward the end of the light-emission,

is of a deeper purple color than that emitted at lower temperatures.

As has been stated, the chlorophane begins to glow at a very low temperature. It reaches its maximum at a point not much above 350°. The other fluorite requires a higher temperature to start the luminescence, and the temperature must be increased to a slightly higher point to completely exhaust its power of emission.

Experimentally, the photography of spectra of luminescences of this intensity offers no difficulty whatever. Patience is necessary, since a large amount of material must be allowed to luminesce in front of the slit of the spectrograph, and the time during which a single crystal of fluorite glows brightly is rather short. Exposures of about four hours were required to yield clear, measurable plates, using the wide-range spectrograph described in a previous paper in this journal (**21,** 83, March, 1905). Longer ones could have been made, but the advantage gained is small, since the continuous diffuse portions increase so rapidly that the lines are not much more clearly differentiated than with the shorter exposure. Much advantage would be gained here by the use of greater dispersion, as the sharp lines could then be brought out while the continuous background remained weak. For this preliminary study, however, the spectrum as a whole is of interest, and the dispersion employed is well suited for the purpose.

After discarding mechanical arrangements of the nature of hot revolving plates and dishes, the simplest possible method of exposure was employed. The material was heated in a test-tube out of range of the slit until it began to glow. It was then held in front of the slit until the glow from the first heating began to grow weak, and it was then reheated, brought back in front of the slit, and so on until the luminescence was exhausted. Fresh material was then put through the same treatment, and the process continued through the time of exposure. Later a small electric furnace was used in the same way, the only advantage which it has over the test-tube being the better control of the temperature. This is in part offset by the difficulty of keeping the brightest luminescence directly in front of the slit when the furnace is used. The heated crystals decrepitate, and break up into smaller cleavage-pieces, and occasionally a heavy explosion within the crystal blows everything out of the furnace, or at least disturbs the position of the main mass of luminescent

material. The test-tube, held in the hand, can be turned so that the brightest place is toward the slit, and in general the cruder method is at least as easy in the end.

The presence of the strong diffuse underlying spectrum makes decision as to the sharpness of lines very difficult, and "intensity" values for lines in the diffuse bands are of course of little value. Intensities are, however, given in the tables on a scale of 1 to 10.

In all of the photographs taken magnesium was used as comparison metal, and lines of the luminescence spectrum which fall near sharp *Mg* lines can therefore be measured with considerable accuracy. It is on the basis of these lines that the values in the column headed "Maximum Error" are given. For example, the line at λ4347, a sharp, strong line of the thermo-luminescence in both varieties of the mineral, lies near the line λ4352 of the *Mg* spark spectrum, and the error of measurement on several plates is not greater than the value given. The line at λ5893 coincides exactly with the unresolved sodium lines in the comparison spectrum.

It would appear proven that the sharp-line portion of the spectrum

TABLE I

CHLOROPHANE FROM AMELIA COURT HOUSE, VA.

Continuous spectrum from violet to red, with maximum in the green-yellow both visually and in photographs. Superimposed over this continuous band the following lines have been measured:

4125	2	diffuse	
4145	2	diffuse	
4315	1	diffuse	
4325	2	sharp	
4335	1	diffuse	
4347	10	sharp	blue group
4365	4	diffuse	
4415	5	nearly sharp	
4457	2		
4525	1	diffuse	
4580	5	sharp	nearly hidden in continuous band
4630	1	diffuse	
4700	2	sharp	
5175		diffuse	
5375	5	sharp	
5400		diffuse	
5435		diffuse	
5500		diffuse	green-yellow group (maxima in the continuous band)
5600		diffuse	
5700		diffuse	
5893		double ?	

TABLE II

FLUOR-SPAR FROM WESTMORELAND, N. H.

4108	1	sharp	4622	1	diffuse
4130	2	diffuse	4658	4	sharp
4150	2	diffuse	4690	2	sharp
4192	1	diffuse	4703	2	sharp
4230	2	diffuse	4715	1	diffuse
4250	2	diffuse	4770	5	nearly sharp
4298	1	diffuse	4800	2	nearly sharp
4312	1	diffuse	4815	3	nearly sharp
4330	2	diffuse	4840	7	diffuse
4347	10	sharp	4892	6	nearly sharp
4365	5	maxima in diffuse band	4903	5	nearly sharp
4370	2		5200		
4382	2	sharp in diffuse band	to		broad band
4398	1		5265		
4415	5	not quite sharp	5375	9	sharp
4450	1	diffuse	5435	4	sharp
4462	2	diffuse	5520	2	sharp
4475	1	diffuse	5720	1	diffuse
4502	2	diffuse	5800	1	diffuse
4540	2	diffuse	5893	5	(sodium lines unresolved?)
4580	4	sharp			

TABLE III

LINES COMMON TO BOTH SPECTRA

Westmoreland	Chlorophane	Mean	Intensity	Maximum Error
4130	4125	4127	2	
4150	4145	4147	2	
4312	4315	4313	1	
4330	4325, 4335	4330	2	
4347	4347	4347	10	± 2 tenth-meters
4365	4365	4365	5	±2 tenth-meters
4415	4415	4415	5	
4462	4457	4460	2	
4580	4580	4580	4	
4625	4630	4627	1	
4690, 4703	4700	4700	2	
5375	5375	5375	9	± 3 tenth-meters
5435	5435	5435	4	± 4 tenth-meters
5893	5893 (?)	5893	5	± 2 tenth-meters

from the two fluorites is the same. All of the strong lines agree in wave-length and relative intensity within the limit of accuracy of the measurements. The diffuse bands of the two spectra are, however, entirely different, and the color of the thermo-luminescence light is due to the preponderance of this series of diffuse bands, the sharp-line portion being in each case comparatively weak.

All attempts to place these sharp lines to the credit of any known elements have been unsuccessful. There are, of course, many coincidences with lines of well-known substances, especially since the accuracy of measurement is so small, but other strong lines of the substance are absent, and one would demand the coincidence of an entire series of lines before admitting that a metal or gas could yield a line spectrum under the conditions of the experiment. The very exact coincidence of the line at λ 5893 with the mean of the two sodium lines suggests the possibility that this may be that pair, unresolved; but it seems to me that resolution into the two constituents would be the very least that could be demanded before deciding that the sodium pair does actually appear under these circumstances. I should therefore wish to reserve any decision on this point until the resolution has been accomplished.

There can be no doubt that these spectra are composites, and that the sources of luminescence, whatever their character, are capable of two distinct kinds of vibration. It seems not too much to conclude that one of these sources gives rise to the diffuse band spectrum, very similar to most spectra of fluorescence and phosphorescence, and entirely different in the two fluorites; while the other source is capable of giving a spectrum in all respects similar to the sharp-line spectra which are usually associated with incandescent gases, the latter source being *common to the two fluorites.*

A generous grant from the Rumford Fund of the American Academy of Arts and Sciences has been of much aid in this work, and a continuance of the investigation is already under way.

Jefferson Physical Laboratory,
Harvard University,
May 1, 1905.

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SUBJECTS.

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AUTHORS